

Water Resources Inventory and Assessment

Bombay Hook National Wildlife Refuge Smyrna, Delaware

February 26, 2013

Prepared by:

Frederic C. Wurster,
U.S. Fish and Wildlife Service
3100 Desert Road
Suffolk, VA 23434

Kirsten J. Hunt &
Rebecca E. Burns
Atkins North America, Inc.
1610 East Millbrook Road
Suite 310
Raleigh, NC 27609

TABLE OF CONTENTS

1	EXECUTIVE SUMMARY	1
1.1	Findings	1
1.2	Recommendations / Further Actions	2
2	INTRODUCTION	2
3	FACILITY INFORMATION	3
4	NATURAL SETTING	6
4.1	Topography and Landforms	6
4.2	Geology	6
4.3	Soils	7
4.4	Hydro-Climatic setting	7
5	INVENTORY	10
5.1	Water Resources	10
5.2	Water-Related Infrastructure	20
5.3	Water Quality	25
5.4	Water Monitoring	27
5.5	Water Rights	36
5.6	Climate Trends	37
6	ASSESSMENT	46
6.1	Water Resource Issues of Concern	46
6.2	Needs and Recommendations	47
7	REFERENCES	48

1 EXECUTIVE SUMMARY

Water Resources Inventory and Assessments (WRIA) are being developed by a national team of hydrologists within the U.S. Fish and Wildlife Service (Service). The purpose of these assessments is to provide reconnaissance-level information on water resources at National Wildlife Refuges (NWRs) and National Fish Hatcheries. The goal of every WRIA is to provide a basic understanding of the water resources that are important to the facility and assess the potential threats to those resources. Data collected in the WRIAs is being incorporated into a national database so water resources can be evaluated nationally and between regions. Information collected for the WRIAs can be used to support Comprehensive Conservation Plans (CCPs), Hydro-Geomorphic Assessments, and other habitat management plans.

1.1 Findings

1. Average total precipitation for the year in the vicinity of Bombay Hook NWR is 45 inches. Precipitation is distributed evenly throughout the year, averaging about 3.7 inches/month.
2. Approximately 83% of the land in the Bombay Hook acquisition boundary is considered wetland habitat using the National Wetland Inventory classification system. Of this, 92% is estuarine and the remaining 8% is freshwater wetland.
3. Up to 80% of the non-tidal streamflow in rivers entering Bombay Hook NWR is derived from shallow groundwater aquifers.
4. Groundwater is the primary source of water for irrigation and municipal purposes in Kent County, DE.
5. The Leipsic River is considered water quality impaired due to excessive levels of bacteria and nutrients and low dissolved oxygen concentrations.
6. Long term climate records indicate air temperature in Dover, DE has increased approximately 3 degrees Fahrenheit (°F) since 1895.
7. There are no statistically significant trends in precipitation patterns or streamflow based on long term climate records in Dover, DE.
8. Long term tide gage data indicates Delaware Bay sea level is rising approximately 3.5 millimeters per year (mm/yr), approximately double the global average of 1.8 mm/yr.

1.2 Recommendations / Further Actions

1.2.1 Evaluate Groundwater Development Adjacent to Refuge

Groundwater development for agricultural purposes is extensive in Kent County, DE and is thought to utilize the same water the refuge's freshwater streams and wetlands rely on. The state of Delaware maintains a database of water production wells. Information on well locations, how the wells were completed, and what they are used for can be requested from the Delaware Department of Natural Resources and Environmental Control (DNREC) Water Supply Section. Recommend that the refuge fill out a Public Record Request with DNREC to get information on the wells near the refuge's boundary. Depending on the number of wells and their proximity to refuge wetlands, this information can be used to identify which, if any, freshwater wetlands may be compromised by groundwater development.

1.2.2 Evaluate Potential Water Quantity and Water Quality Monitoring Sites at Bombay Hook NWR

Although some water quality monitoring is taking place in groundwater and surface water locations off refuge, there is little monitoring taking place on refuge water resources. The condition of water entering the refuge via Finis Branch seems particularly important since it is the primary stream contributing surface water to the refuge's impoundments. Additionally, the refuge may want to consider monitoring salinity in freshwater wetlands susceptible to saltwater intrusion.

1.2.3 Review Hydrologic Impacts of Refuge Infrastructure

Infrastructure like water control structures, culverts, bridges, ditches, and dikes affect water movement through refuge wetlands. In some cases poorly designed infrastructure or legacy infrastructure from pre-refuge land uses can create problems that compromise habitat management. The refuge's infrastructure should be evaluated from a hydrologic perspective to identify potential problem features. This information will be helpful as the refuge seeks to develop plans for adapting to climate change and rising sea levels.

2 INTRODUCTION

This Water Resource Inventory and Assessment (WRIA) Summary Report for Bombay Hook National Wildlife Refuge (NWR) describes current hydrologic information, provides an assessment of water resource issues of concerns, identifies water resource needs, and makes recommendations regarding refuge water resources. The information contained within this report and supporting documents will be entered into the national WRIA database.

Together, the national WRIA database and summary reports are designed to provide a reconnaissance level inventory and assessment of water resources on National Wildlife

Refuges and National Fish Hatcheries. A national team of U.S. Fish and Wildlife Service (Service) Water Resource staff, Environmental Contaminants Biologists, and other Service employees developed the standardized content of the national WRIA database and summary reports.

The long term goal of the National Wildlife Refuge System (NWRS) WRIA effort is to provide up-to-date data on a facility's water quantity and quality in order to protect adequate supplies of clean and fresh water. An accurate water resources inventory is essential to prioritize issues and tasks, and to take prescriptive actions that are consistent with the established purposes of the refuge. Reconnaissance-level water resource assessments evaluate water rights, water quantity, known water quality issues, water management, potential water acquisitions, threats to water supplies, and other water resource issues for each field station.

WRIAs are recognized as an important part of the NWRS Inventory and Monitoring (I&M) Program and are outlined in the I&M Draft Operational Blueprint as Task 2a. Hydrologic and water resource information compiled during the WRIA process will help facilitate the development of other key documents for each refuge including Hydrogeomorphic Analyses (HGM) and Comprehensive Conservation Plans (CCP).

Bombay Hook NWR WRIA

This WRIA Summary Report for Bombay Hook NWR incorporates hydrologic information compiled between April 2012 and February 2013. The report is intended to be a reference for ongoing water resource management and strategy development. However, the document is not meant to be exhaustive or a historical summary of activities on Bombay Hook NWR. This WRIA was developed in conjunction with refuge staff under a contract with Atkins North America, Inc. in 2012-2013.

3 FACILITY INFORMATION

Bombay Hook National Wildlife Refuge

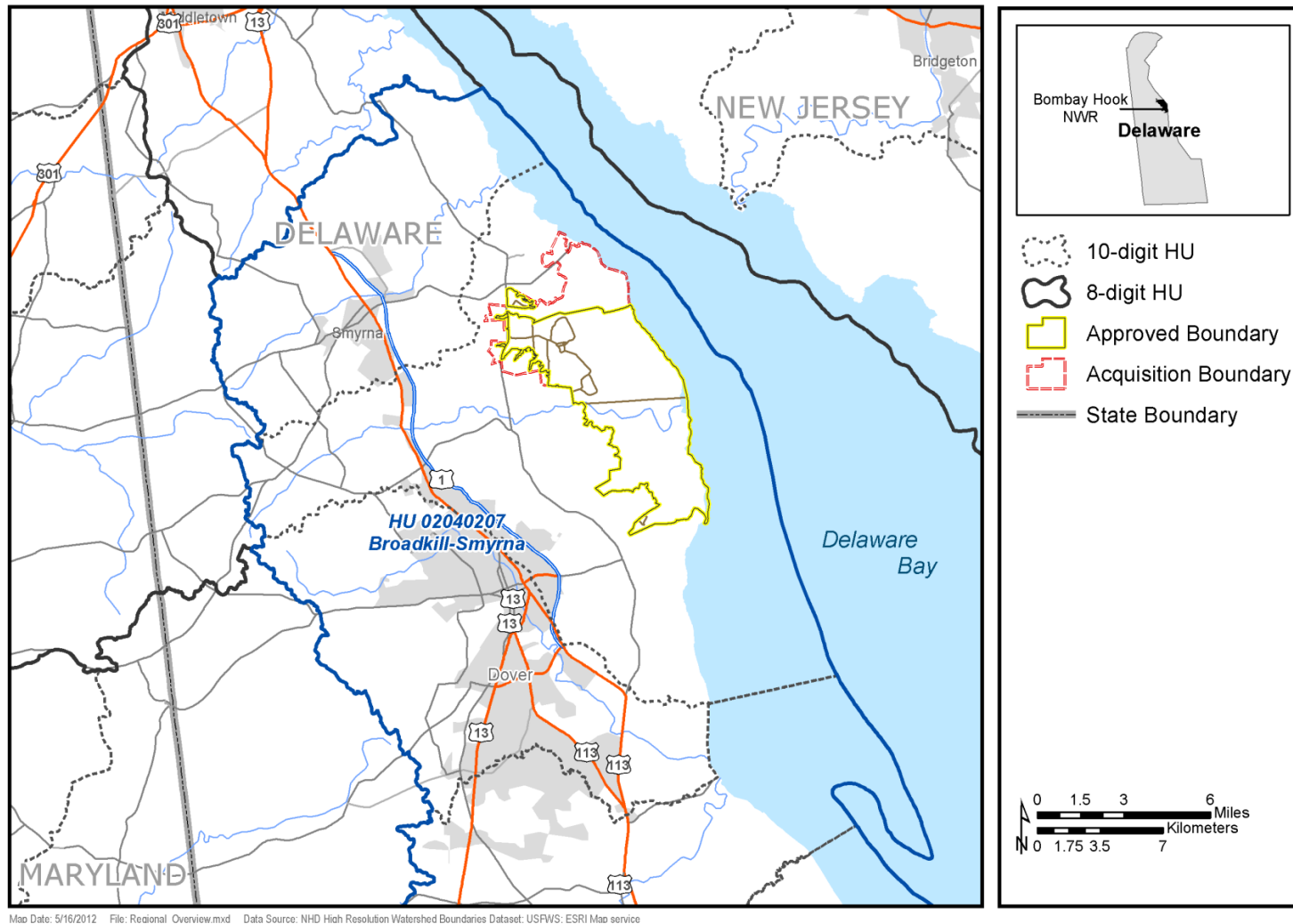
Bombay Hook National Wildlife Refuge (NWR) was established in 1937 as a link in the chain of refuges extending from Canada to the Gulf of Mexico. It is primarily a refuge and breeding ground for migrating birds and other wildlife. Authority for managing and acquiring the land for the National Wildlife Refuge System falls under the Migratory Bird Conservation Act, Fish and Wildlife Act of 1956, and the Emergency Wetlands Resources Act of 1986. The refuge is composed primarily of tidal salt marsh and protects approximately 16,597 acres¹ in Kent County, Delaware (Figure 1). An additional 4,566 acres to the north and west of the current refuge property has been identified for future acquisition.

¹ For the purposes of this report, all units are expressed in English measures, unless citing information from a primary source where the native data are presented in metric units. In those cases, the English unit conversions are also provided.

There are no federally listed threatened/endangered species present on the refuge.

Primary water resources of concern include salt marsh habitat and freshwater habitat maintained in the form of impoundments and upland moist soil units. Salt marsh habitat is at risk for loss due to sea level rise. Most of the freshwater impoundments and moist soil units rely on rainfall runoff rather than streamflow in order to maintain water levels, and are at risk of adverse effects of climate change and drought.

Secondary concerns apply to the water quality of streams which drain agricultural areas outside the refuge boundaries, as well as potential pollutants on two portions of the refuge acquired from the United States Air Force which had been used as bombing ranges in the past.



4 NATURAL SETTING

4.1 Topography and Landforms

Bombay Hook NWR lies in the relatively flat Embayed Atlantic Coastal Plain physiographic province of the Delmarva Peninsula, adjacent to Delaware Bay. Delaware Bay is the major estuary outlet of the Delaware River. It spans 782 square miles between the states of Delaware and New Jersey, and represents a zone of freshwater-saltwater mixing into the Atlantic Ocean.

Land within the boundaries of Bombay Hook NWR is typical of the province, composed primarily of tidal salt marsh and mud flats with small areas of upland. Ground surface elevations on the refuge are lower than 10 feet above sea level.

The U.S. Geological Survey (USGS) has developed a national dataset of hydrologic units (Seager et al. 1994). Hydrologic units are based on watershed boundaries and are assigned Hydrologic Unit Codes (HUC). Two-digit HUCs are applied to the largest areas, which are defined as regions. Regions are subdivided into 4-digit subregions, which are then further subdivided down to smaller areas. For the purposes of this WRIA, HUCs at the 8-digit (subbasin) and 10-digit (watershed) scales will be referenced. These HUCs are important because they are used by many federal and state agencies to track water monitoring and regulatory activities.

Bombay Hook NWR is located within the Broadkill/Smyrna (8-digit HUC: 02040207; 10-digit HUC: 0204020702) hydrographic subbasin (Figure 1). The State of Delaware uses the 10-digit HUC boundaries to define the watershed boundaries of the state's rivers for regulatory and planning purposes. Bombay Hook falls entirely in the Leipsic River watershed. The Leipsic flows from west to east and roughly bisects the refuge into a northern 2/3 and southern 1/3.

4.2 Geology

Bombay Hook is found in the Atlantic Coastal Plain of Delaware. The coastal plain is composed of sediments that have been deposited by the erosion of the Appalachian Mountains. The thickness of the sediments in the coastal plain approaches 10,000 ft in the vicinity of Bombay Hook NWR (Figure 2). Underlying these sediments is bedrock that is thought to be of the same origin as rocks found in the Piedmont of northwestern Delaware.

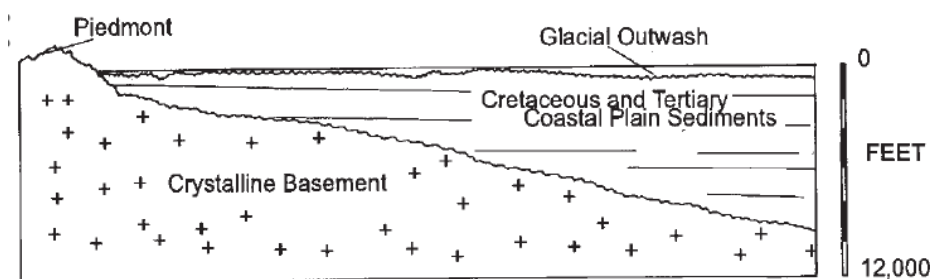


Figure 2. Generalized cross-section of the Atlantic Coastal Plain. From Delaware Geological Survey's "A Summary of the Geologic History of Delaware" (DGS undated).

4.3 Soils

Soils at Bombay Hook NWR are predominantly hydric (Table 1). There are 24 unique soil unit types; however, two soils, the Broadkill-Appoquinimink Complex and Transquaking and Mispillion group, dominate, comprising 70% of the area within the refuge boundary. Both units are tidal marsh soils composed of peat and mucky silt loams produced from a combination of decomposing marsh vegetation and marine sediments. They are flooded frequently and have a relatively unconsolidated structure.

Table 1. Acreage of hydric soils at Bombay Hook NWR. From NRCS Soil Data Mart (NRCS 2011).

	Owned Boundary	Acquisition Boundary
Hydric Status	Acres	Acres
All hydric	11897.9	14466.4
Not hydric	267.3	279.1
Partially hydric	2244.2	3834.9
Total	14409.4	18580.3

4.4 Hydro-Climatic setting

Climate at Bombay Hook is characterized by warm, humid summers with frequent thunderstorms and cold winters with snowfall.

4.4.1 PRISM Monthly Normals

The U.S. Department of Agriculture's (USDA) official climatological data comes from the PRISM (Parameter-elevation Regressions on Independent Slopes Model) climate mapping system, developed by Dr. Christopher Daly, of the PRISM Climate Group at Oregon State University. PRISM is a unique knowledge-based system that uses point measurements of precipitation, temperature, and other climatic factors to produce continuous, digital grid estimates of monthly, yearly, and event-based climatic

parameters. Data are continuously updated, and can be downloaded for a specified region, or by latitude/longitude.

The 1971-2000 climatological normals for Bombay Hook NWR (Table 2) indicate an annual average of approximately 45 inches of rain, evenly distributed throughout the year. Average monthly precipitation is 3.71 inches. Temperatures range from an average minimum of 25 °F (-3.9 °C) in January to an average maximum of 87.4 °F (30.8 °C) in July.

Table 2. PRISM Monthly Normals (1971 – 2010) for Bombay Hook NWR.
GPS coordinates: -75.431099W, 39.256183N (PRISM Climate Group 2010)

Month	Precipitation (In)	Max Temperature (F)	Min Temperature (F)
January	3.74	43	25
February	2.99	46	26.6
March	4.27	54.9	33.8
April	3.47	65.3	42.1
May	4.25	74.8	52
June	3.65	82.9	61.1
July	3.74	87.4	66.3
August	4.56	85.5	64.8
September	4.34	79.4	57.9
October	3.21	68.7	46.1
November	3.18	58	37.6
December	3.48	47.7	29.4
Total Precipitation	44.88		
Average Temperature		66.1	45.2

4.4.2 USGS Hydro-Climatic Data Network (HCDN)

The HCDN is a network of USGS stream gaging stations that are considered well suited for evaluating trends in stream flow conditions. Sites in the network have periods of record that exceed 20 years and are located in watersheds that are relatively undisturbed by surface water diversions, urban development, or dams.

The closest HCDN gage to Bombay Hook NWR is located in Mannsboro, VA. Because the station is located in a different Hydrologic Unit than Bombay Hook, we chose to analyze gage information from a closer station, on the St. Jones River in Dover, DE.

Although the station is not a HCDN gage, it does fall within the same 8-digit Hydrologic Unit as Bombay Hook NWR, and has a suitable period of record for discharge analysis (1959 – 2012). Seasonal discharge data for the St. Jones stream gage are presented in Figure 3.

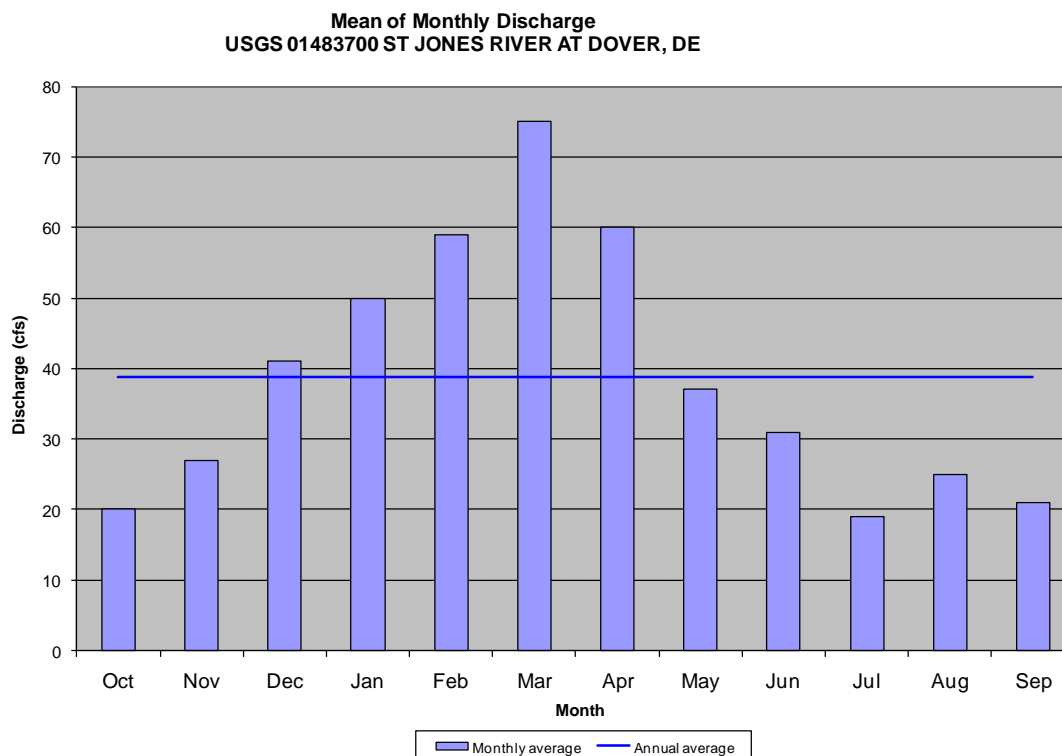


Figure 3. Average monthly discharge from the St. Jones River near Dover, DE. From data collected between 1959 – 2012.

Trends presented in Figure 3:

Average monthly discharge shows a classic seasonal pattern. Discharge increases steadily through the late-Fall, peaking in early spring before the onset of the growing season.

Lowest flow conditions of the year occur in the summer months, when evapotranspiration is at its highest.

Average discharge for the year is approximately 38 cubic feet per second (cfs).

Streamflow in Delaware's coastal plain is strongly influenced by precipitation patterns and evapotranspiration during the growing season. Like all rivers, runoff rises and falls with changes in precipitation. However, in the coastal plain, it is estimated that 60 – 80% of the non-tidal streamflow comes from groundwater (DNREC 2005). Shallow groundwater acts as a reservoir that helps maintain freshwater flow in coastal plain rivers. Therefore natural and human activities that remove water from groundwater aquifers can

reduce the non-tidal streamflow. Evapotranspiration and municipal and agricultural groundwater use can decrease streamflow during the growing season. When these water demands decrease during the winter months, flow rates tend to increase again, eventually peaking in the early spring (Figure 3).

The seasonal distribution of runoff influences the salinity in the estuarine sections of coastal plain rivers. The high flows of the winter and spring generate lower salinities at the river's mouth. During the growing season when freshwater flows decrease, salt water moves from the Bay inland up the river channels.

5 INVENTORY

This section of the WRIA summarizes basic information on the refuge's water resources, water-related infrastructure, water quality, water monitoring, water rights, and climatic trends. Data from this section is incorporated into the national WRIA database.

5.1 Water Resources

Surface water features include lakes, ponds, springs, impoundments, reservoirs, rivers, streams, and creeks. Groundwater resources include regional and local aquifers that are important to the surface water resources of the refuge. Also included are wetlands identified in National Wetland Inventory maps that cover the refuge area.

5.1.1 Rivers / Streams / Creeks

The WRIA relies on the U.S. Geological Survey 1:24,000 scale National Hydrography Dataset (NHD) to inventory streams at Bombay Hook NWR (Table 3, Figure 4). The focus of the preliminary analysis is on named NHD features because they tend to be the largest and, theoretically, of most interest to Service facilities.

For most of their length, streams at Bombay Hook are considered estuaries with daily tidal fluctuations and brackish water. In the largest streams, the tidal range is between 4.52 and 5.58 feet, with a range of 3.28 ft or less in the smaller guts. On many streams, tide gates, levees, low-head dams, and roads control how far brackish water extends upstream. The headwaters of Kent County streams are typically low-gradient seeps with poorly defined channels that flow towards Delaware Bay.

Table 3. Named creeks and streams from the USGS 1:24,000 National Hydrography Dataset. Includes features on or within Bombay Hook NWR's approved acquisition boundary. Miles above the estuary are calculated by measuring the stream length upstream from the NWI estuarine wetland classification.

Stream Name	Miles in Acquisition Boundary	Miles Upstream of Estuary	% of Miles Upstream of Estuary	Stream Name (continued)	Miles in Acquisition Boundary	Miles Upstream of Estuary	% of Miles Upstream of Estuary
Duck Creek	10.8	0	0	Bank Ditch	0.8	0	0
Leipsic River	5.4	0	0	Broad Gut	0.8	0	0
Green Creek	4.5	0	0	Flat Gut	0.8	0	0
Mahon River	4.1	0.6	15	Little Fork	0.7	0	0
Shearneck Gut	3.2	0	0	Boat Gut	0.7	0	0
Finis Branch	2.3	2.3	100	Mikes Ditch	0.7	0	0
Herring Branch	2.2	0.5	23	Slooch Ditch	0.7	0	0
Old Creek	1.9	0	0	Salt Pond Ditch	0.6	0	0
Old Womans Gut	1.9	0	0	Drum Gut	0.5	0	0
Raymond Gut	1.8	0	0	Joes Hole	0.5	0	0
Hawkey Branch	1.7	0.2	12	Marshtown Gut	0.4	0	0
Simons River	1.6	0	0	East West Canal	0.4	0	0
Myrkie Gut	1.5	0	0	Cove Pond Ditch	0.3	0	0
Kellys Ditch	1.5	0	0	Lees Ditch	0.3	0	0
Dutch Neck Canal	1.4	0	0	Terrapin Gut	0.3	0	0
Bay Gut	1.2	0	0	Denver Gut	0.2	0	0
Cedar Gut	1.2	0	0	Jenkins Ditch	0.2	0.1	50
Sluice Ditch	1.0	0	0	Indian Gut	0.1	0.1	100
North South Canal	1.0	0	0	Wier Gut	0.1	0	0
Hay Ditch	0.9	0	0	Muddy Branch	0.1	0.1	100
Total					60.3	3.9	-

5.1.2 Canals and Drainage Ditches

The refuge contains extensive areas of ditches, both in the salt marsh and in the upland areas; however, the aggregate length of ditches on the refuge is unknown. Historically, salt marshes were ditched for agriculture, navigation and mosquito control (see Section 5.2.5). Areas that were grid ditched for mosquito control are concentrated in the southern portions of the refuge. In the northeast area of the refuge, a large navigation channel was dredged in the 1800s and many smaller ditches were dug for firebreaks (Bombay Hook NWR staff, personal communication).

Many ditches were dug in upland areas to support row crop agriculture. These ditches are widespread, particularly in the northwest section of the refuge (i.e., Dutch Neck). The refuge is working to map the extent of relict ditches and wants to restore seasonal wetland habitat in some fields by plugging these ditches.

5.1.3 Lakes, Ponds, and Impoundments

Most open-water features at Bombay Hook are man-made waterbodies. Many are sand and gravel pits that have filled with water, small drainages that have been dammed, or ponds that formed when roads blocked surface water runoff. For this preliminary analysis the WRIA focuses on named ponds and lakes in the NHD dataset (Table 4 and Figure 4). Total acreage of the named ponds and lakes is 520 acres. The NHD dataset identifies an additional 321 ponds inside the acquisition boundary that have no name. These are mostly small features with an average size of 3.9 acres. Total acreage of named and unnamed ponds is approximately 1245 acres, or 7.7% of the area in the acquisition boundary (16,597 acres). The areas classified by the NHD as unnamed lakes/ponds are probably open water areas in the marsh as the refuge has few, if any, nontidal ponds. These open areas, which began to appear in the 1920s and 30s, are maintained by snow geese grazing and ice (Bombay Hook NWR staff, personal communication).

Table 4. Acreage of named ponds and swamp/marsh habitat identified in the USGS National Hydrography Dataset (NHD). Includes features within Bombay Hook NWR's approved acquisition boundary.

Pond Name	Acres
Bear Swamp Pool	147.5
Log Pond	2.9
Raymond Pool	62.0
Shearneck Pool	307.2
Unnamed lakes/ponds	1244.7
Total	1764.3

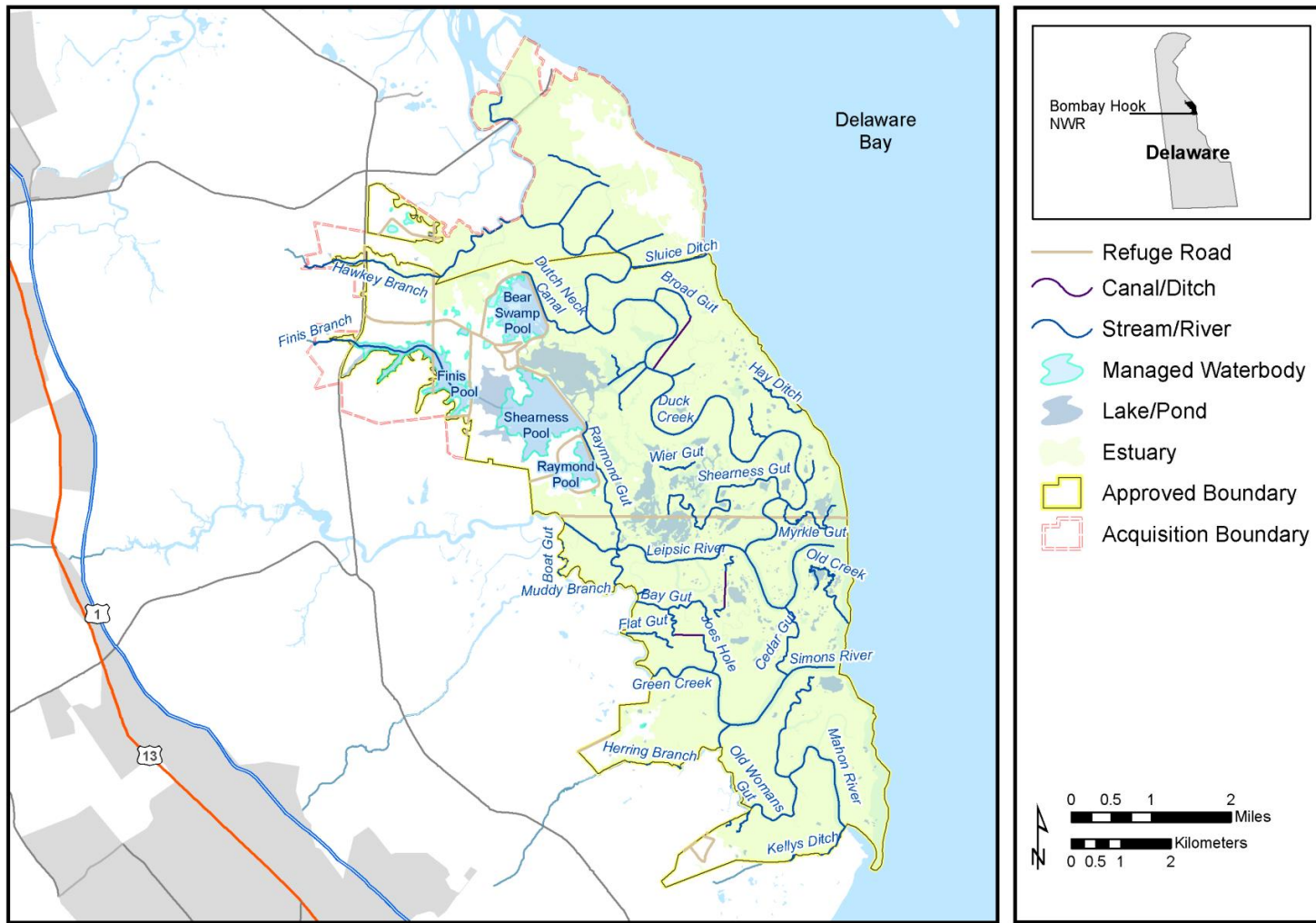


Figure 4. Named creeks, streams, and waterbodies from 1:24,000 USGS National Hydrography Dataset in the Bombay Hook NWR acquisition boundary.

5.1.4 Springs / Seeps

Springs and seeps are not considered significant water resources of concern at Bombay Hook NWR.

5.1.5 Wetlands

The National Wetland Inventory (NWI) is a branch of the U.S. Fish and Wildlife Service established in 1974 to provide information on the extent of the nation's wetlands (Tiner 1984). NWI produces maps of wetland habitat as well as reports on the status and trends of the nation's wetlands. Using the *Classification of Wetlands and Deepwater Habitats of the United States* (Cowardin et al. 1979) wetlands have been inventoried and classified for approximately 90% of the conterminous United States and approximately 34% of Alaska. Cowardin's classification places all wetlands and deepwater habitats into 5 "systems": marine, estuarine, riverine, lacustrine, and palustrine. Most of the wetlands in the United States are either estuarine or palustrine (Tiner 1984). The two predominant wetland classes at Bombay Hook NWR are defined in Cowardin et al. (1979) as:

Estuarine: the Estuarine System consists of deepwater tidal habitats and adjacent tidal wetlands that are usually semi-enclosed by land but have open, partly obstructed, or sporadic access to the open ocean. The Estuarine System extends (1) upstream and landward to where ocean-derived salts measure less than 0.5% during the period of average annual flow; (2) to an imaginary line closing the mouth of a river, bay, or sound; and (3) to the seaward limit of wetland emergents, shrubs, or trees where they are not included in (2).

Palustrine: the Palustrine System includes all nontidal wetlands dominated by trees, shrubs, persistent emergents, emergent mosses or lichens, and all such wetlands that occur in tidal areas where salinity due to ocean derived salts is below 0.5% (e.g., inland marshes, bogs, fens, and swamps)

The different systems can be broken down into subsystems, classes and hydrologic regimes based on the wetland's position in the landscape, dominant vegetation type, and hydrology.

Approximately 83% (17,637 acres) of the land in the acquisition boundary is considered wetland using NWI's classification. Only 8% (1,673 acres) of these wetlands are considered freshwater wetlands the remaining 92% being Estuarine. Estuarine Emergent (12,568 acres or 59%), Estuarine Subtidal (2,885 acres or 14%), and Palustrine Forested (487 acres or 2%) are the most extensive wetland types within the acquisition boundary and are typical of the land in the Delaware Bay Division (Table 5 and Figure 5).

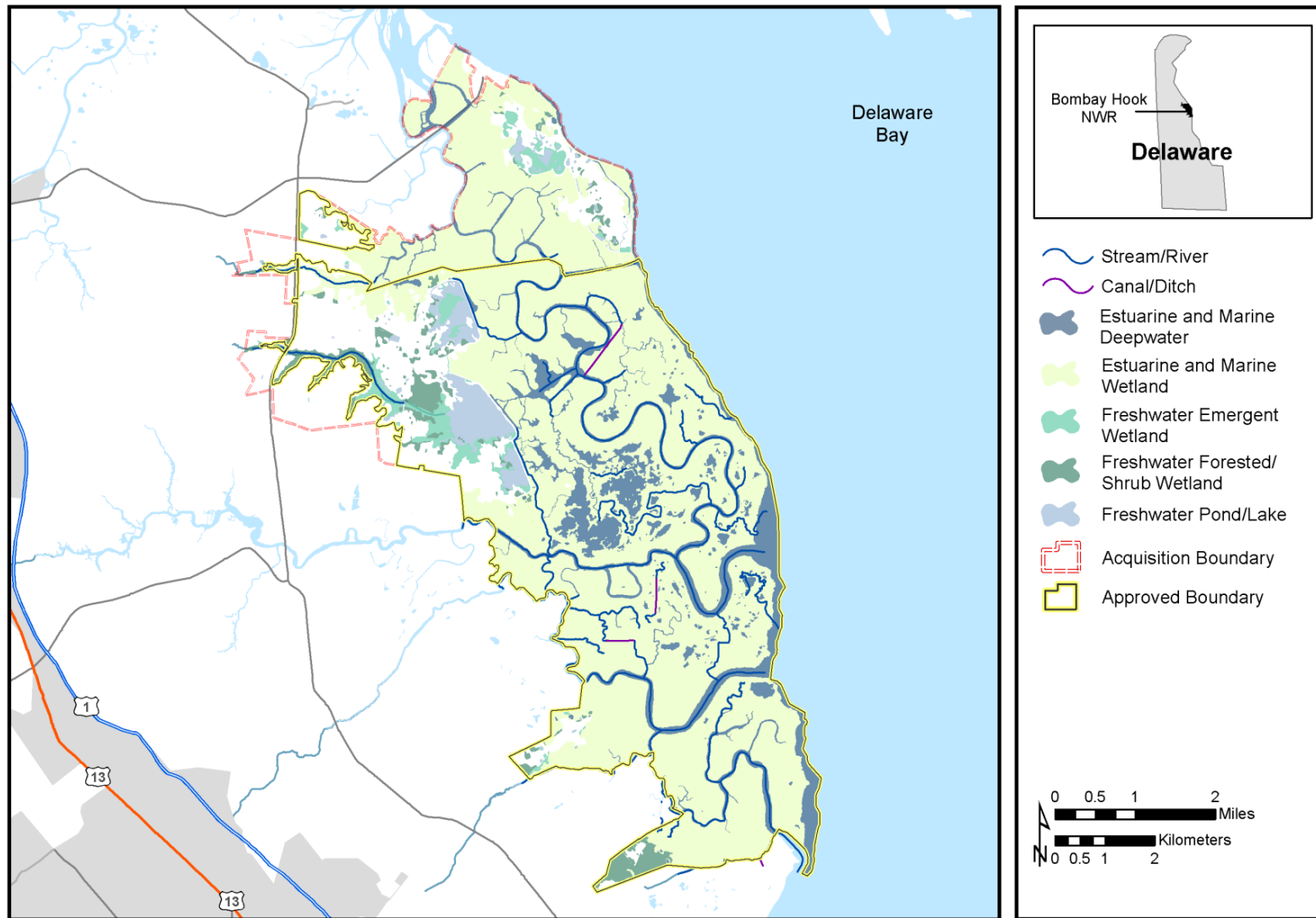


Figure 5. National Wetland Inventory wetlands in the Bombay Hook NWR acquisition boundary.

Table 5. Wetland habitat delineated by the National Wetland Inventory (NWI) inside the Bombay Hook NWR acquisition boundary.

NWI	Alias	Acres within Acquisition Boundary	Percent of Total
Estuarine Aquatic Bed	Coastal Algal Bed	388.0	1.8
Estuarine Emergent	Emergent salt marsh	12561.7	59.4
Estuarine Shrub/Scrub	Shrub dominated salt marsh	14.7	0.1
Estuarine Unconsolidated Shore	Mudflat	114.4	0.5
Estuarine Subtidal	Deepwater	2885.0	13.6
Lacustrine	Lake, permanently flooded	78.7	0.4
Palustrine Aquatic Bed	Inland Algal Bed	50.9	0.2
Palustrine Emergent Marsh	Freshwater emergent marsh	470.3	2.2
Palustrine Forested	Forested wetland	487.3	2.3
Palustrine Shrub/Scrub	Shrub-dominated wetland	133.2	0.6
Palustrine Unconsolidated Bottom	Ponds	453.2	2.1
Upland	Upland	3525.4	16.7
Total		21162.7	100

5.1.6 Groundwater

Bombay Hook overlies the Northern Atlantic Coastal Plain Aquifer System. The aquifer is described generally in the USGS groundwater atlas of the United States (Trapp and Horn 1997). In general, the aquifer system under the Bombay Hook National Wildlife Refuge is comprised of unconsolidated gravel, sand, and silt separated by layers of less permeable silts and clays.

Bombay Hook is located in an area where unconsolidated coastal plain sediments rest upon basement rock (Figure 2). These sediments are derived from the erosion of the Appalachian Mountains and have been deposited over the eons by rivers and streams flowing from the mountains to the Atlantic Ocean. Additionally, at times when the sea level was higher than it is today, marine sands were deposited across much of what is now the coastal plain. As sea levels have fluctuated over the last several million years the area has experienced different cycles of riverine and marine depositional processes. Freshwater stored in these different deposits create aquifers that are utilized for municipalities, industry, and agriculture. Groundwater is the primary source of freshwater for human activities in Delaware and demands placed on the state's groundwater resources are high.

The aquifer of most interest to wetland and stream resources near Bombay Hook is the Columbia Aquifer. This aquifer is a large, unconfined, surficial aquifer that covers almost all of Kent County. It is composed of sands and gravels deposited during ice ages that began more than 2.0 million years ago. The thickness of the aquifer is variable,

ranging from 10 to 150 ft and the depth to the water table ranges between 5 and 20 ft below ground surface (Andres 2001). The Columbia Aquifer is a major source of water used for municipal, agricultural, and industrial uses in Kent County and contributes between 60 and 80 percent of total non-tidal streamflow (DNREC 2005). Because the sediments of the Columbia Aquifer are very permeable, the water in the aquifer is recharged readily by rainfall. However, the high permeability also facilitates the rapid transfer of surface contaminants into the aquifer (DNREC 2005).

Because of the important role groundwater resources play in Delaware's water supply, the state has adopted regulations to protect areas where groundwater recharge potential is high. These zones have been mapped by the Delaware Geological Survey (Andres 2002) and are displayed relative to Bombay Hook NWR in Figure 6. Zones of "high" and "good" groundwater recharge potential are areas where the sediments are highly permeable and precipitation infiltrates readily into groundwater aquifers. Groundwater probably contributes more water to surface water features near these zones than in "poor" recharge zones. The areas of high recharge potential are west of the refuge, south of the Leipsic River, and near the headwaters of Herring Branch and Old Woman Gut on the southern end of the refuge.

The widespread use of groundwater for municipal purposes has led to water level declines in some Kent County aquifers near the city of Dover (dePaul et al. 2009). Additionally, the acreage of irrigated cropland in Kent and Sussex counties has been increasing (DNREC 2011) and refuge staff have observed more groundwater wells being drilled near the refuge in the last 2-3 years. Most of the wells used for irrigating cropland are thought to be tapping the Columbia Aquifer (Cocke personal communication). Although, Bombay Hook NWR does not pump groundwater to maintain wetland habitat there is concern that groundwater pumping on neighboring properties could detrimentally affect refuge wetlands.

In order for groundwater development to affect wetlands and streams there must be: 1) a connection between the aquifer and surface water features and, 2) groundwater pumping must be lowering the water level in the aquifer connected to the surface water features. Interactions between surface water and groundwater are most common in surficial aquifers like the Columbia, where water levels are close to the ground surface. Given the municipal, industrial, and irrigation demands on the Columbia Aquifer it seems likely that groundwater development off-refuge can affect surface water and groundwater inputs to refuge wetlands. From Table 3 and Table 4, most of the refuge wetlands and streams are tidal estuarine systems. Therefore, any impacts to freshwater resources from reduced streamflow will probably affect a small portion of the refuge's habitat, most of which is concentrated on the western edge of the refuge property.

5.1.7 Groundwater Well Information

The State of Delaware's Division of Water, Well Permits Branch provides oversight and technical review for well construction and water well permit applications where wells are

located near problem sites. It also maintains a database on the construction and status of all wells for which a well construction or use permit has been issued.

Although there are undoubtedly numerous domestic and irrigation wells in the vicinity of Bombay Hook NWR, a map of their location was not prepared for this report. A map of irrigation well densities shows 1 to 10 wells in the modified grid within the refuge (Map 2.5-13 in DNREC 2005). One public supply well for the refuge was constructed in 2003 in the Confined Cheswold Aquifer (DNREC 2004; Map ID 12 in Figure 10). Wells were also bored in the southeastern portion of the refuge, along the shoreline; however, their locations are unknown (Bombay Hook NWR staff, personal communication). Additional work, beyond the scope of the current document, is necessary to review the distribution and potential impacts on refuge water resources.

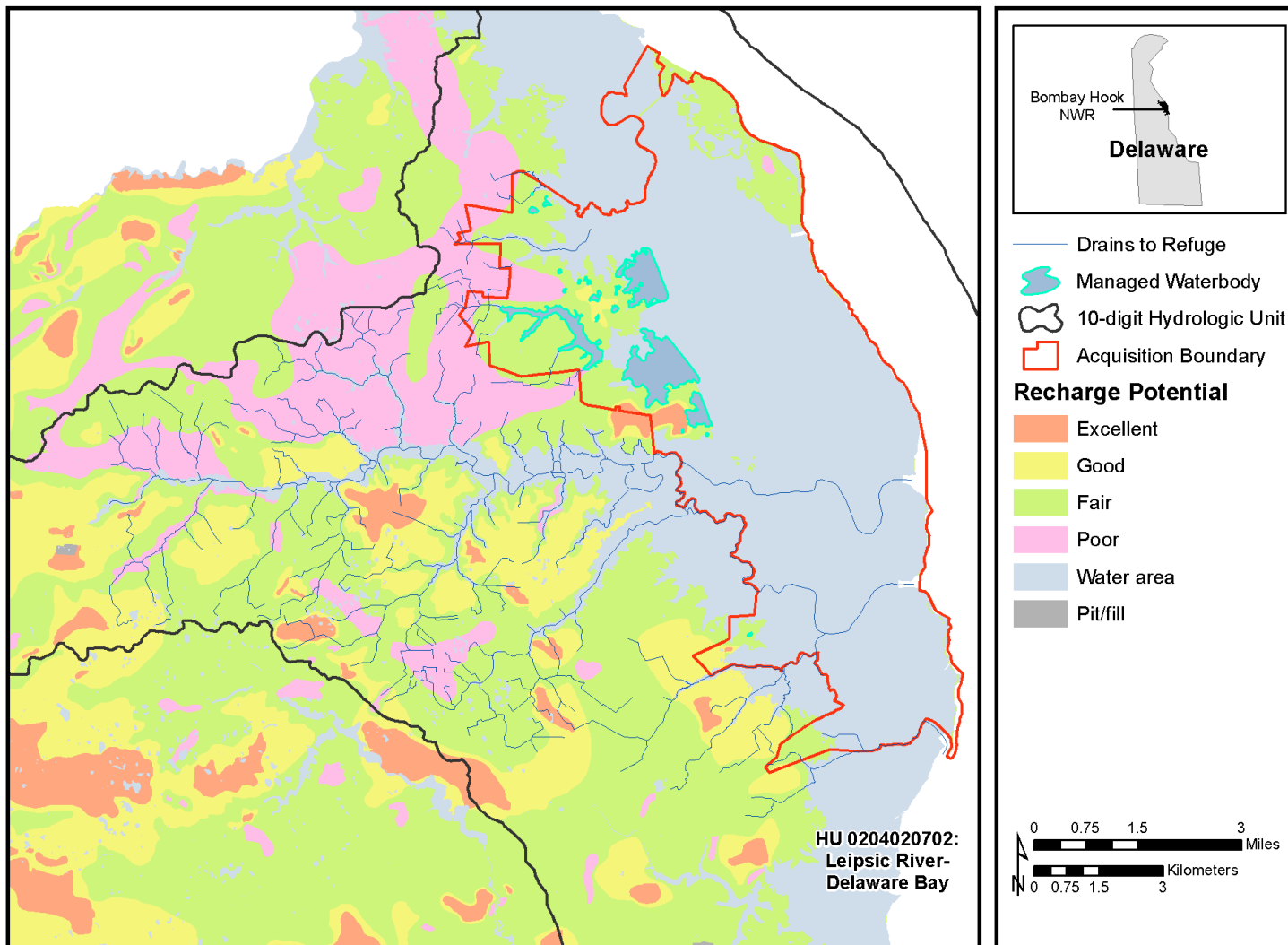


Figure 6. Groundwater recharge potential near Bombay Hook NWR. From Andres et al. (2002).

5.2 Water-Related Infrastructure

Water-related infrastructure refers to the assets at a refuge that create or support refuge water resources and objectives. Examples include impoundments for waterfowl habitat, water control structures and water supply wells used to maintain wetland habitat. Many of these types of features are accounted for in the National Wildlife Refuge System's Service Asset Maintenance Management System (SAMMS) database.

Bombay Hook NWR's water-related infrastructure supports management of habitat for migratory waterfowl. Refuge wetlands are being manipulated by refuge staff using infrastructure such as dikes, water control structures, or water supply wells.

5.2.1 Impoundments

Central to the refuge's mission of providing habitat for waterfowl is the maintenance of freshwater management units (WMUs). Four major WMUs are currently maintained on Bombay Hook NWR: Finis Pool, Shearneck Pool, Bear Swamp Pool, and Raymond Pool. Finis Pool is the only major impoundment with a regular supply of fresh water from Finis Branch. The water level in all other impoundments is dependent on rainfall, runoff that enters the refuge from uplands to the west, and managed diversions where water control structures are present. Figure 7 shows the relationship between major impoundments, water control structures, diversion ditches, and the surrounding uplands and salt marsh. Table 6 details WMUs listed in the 1994 Bombay Hook NWR Marsh and Water Management Plan (USFWS 1994).

Prior to the 1980s, impoundment water level management plans called for static, high levels. More recently, specific water management practices are varied slightly between WMUs according to targeted species, desired conditions, and climate considerations. For the purposes of this document, a generalized seasonal and spatial account is provided, with the caveat that management practices are re-evaluated yearly.

Water levels in the impoundments are generally highest in the winter and early spring. Management focuses on a slow (less than 3 inches per week) drawdown timed to begin mid-spring with the arrival of migratory waterfowl. This drawdown continues into the summer months, in order to facilitate growth of food sources for a variety of species. Impoundments are re-flooded in the fall, again in synchrony with waterfowl migration. Water levels in Finis Pool are not managed as actively as in the other three WMUs (Bombay Hook NWR staff, personal communication).

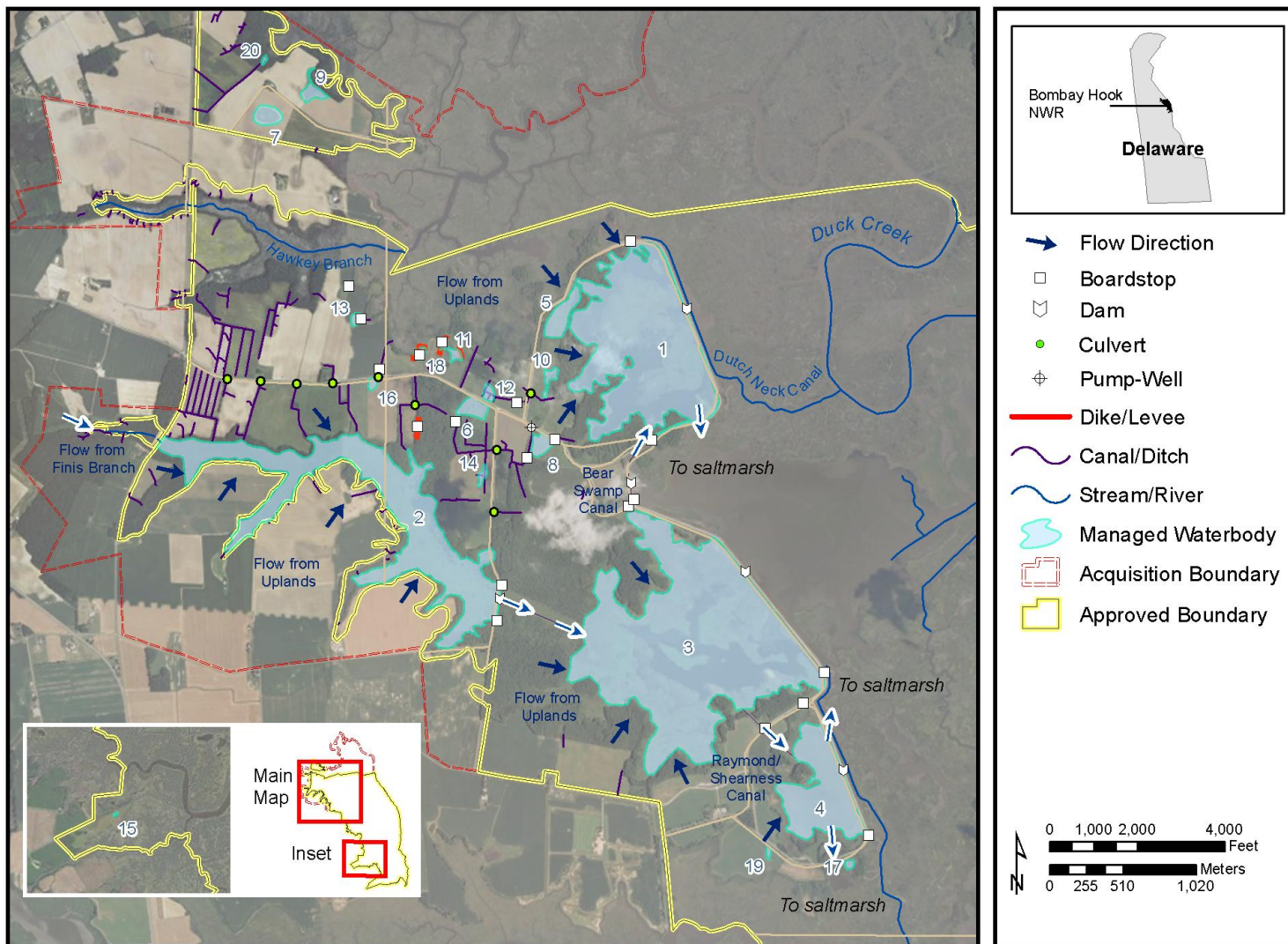
In the 1990s, nine additional impoundments known as Moist Soil Units (MSUs) were created as sources of alternate habitats. All are less than a few acres and dependent on rainfall and runoff with no formal outlets. An impoundment with a water control structure was also created in the Steamboat Landing Tract in the 1990s (Map ID 15 in Table 6 and

Figure 7); however, it is not functional (Bombay Hook NWR staff, personal communication).

The mucky, peaty nature of impoundment bottoms makes them unsuitable for the mechanical management of invasive plants during periods of water drawdown. Refuge management instead utilizes a combination of water level control, burning, and herbicide application practices to control unwanted plant growth within freshwater impoundments.

Table 6. Managed Water Units at Bombay Hook NWR.

Map	Wetland Unit Name	Acres
1	Bear Swamp Pool	212.5
2	Finis Pool	183.9
3	Shearneck Pool	374.5
4	Raymond Pool	65.6
5	WMU-5	10.0
6	Big Woods Pond	5.6
7	Field 307 MSU (WMU-13)	5.3
8	B-Pool (WMU-6)	4.3
9	Field 308 MSU (WMU-14)	3.6
10	Ducks Unlimited Pond (WMU-15)	2.3
11	Field 22 Pool (WMU-8)	2.1
12	Field 23 MSU	1.8
13	Field 108 MSU	1.4
14	Fields 25/26 MSU	1.3
15	Steamboat Pool (Field 503)	1.3
16	Field 20 MSU (WMU-10)	1.1
17	Field 16 Pond	0.9
18	Field 19 Pond (Straughn Pool, WMU-7)	0.8
19	Field 4 MSU (Cottman Pool, MSU-12)	0.6
20	Fischer Woods Pond	0.4



Map Date: 2/6/2013 File: FD WC structures.mxd Data Sources: NHD High Resolution Flowlines; USFWS Water Management structures, managed waterbodies, and boundaries; ESRI Imagery Service.
Figure 7. Wetland impoundments and flow paths between impoundments at Bombay Hook NWR.

5.2.2 *Water-control structures*

Approximately 4.5 miles of dikes enclose the major impoundments on the Refuge. Water levels in the four major impoundments on Bombay Hook NWR are controlled using a series of box culverts, canals, and stop log water control structures (Table 7, Figure 7).

Freshwater from Finis Pool, fed by Finis Branch, enters Shearness Pool through two structures built into Finis Dike. Shearness Pool is connected to both Bear Swamp Pool and Raymond Pool via canals. Due to the elevations of the pools, water can only be diverted from Shearness Pool into Raymond Pool when the water level in Shearness Pool is above 2 feet, which usually occurs only during late winter and spring. When water levels are more than 3 ft in Shearness Pool water can be diverted into Bear Swamp Pool. However, these conditions rarely exist under current management conditions. In addition to the above mentioned structures, all four impoundments have water control structures allowing for the discharge of fresh water directly into the estuarine marsh. Currently there is tidal flow in and out of Shearness Pool because of a broken WCS, which the refuge plans to replace (Bombay Hook NWR staff, personal communication).

5.2.3 *Off-Refuge Surface Water Diversions*

Off-refuge surface water diversions upstream of Bombay Hook NWR are not large enough to warrant consideration in the WRIA.

5.2.4 *Off-Refuge Surface Water Sources*

Finis Branch is the only freshwater creek with headwaters outside refuge boundaries that supplies water to one of the managed impoundments (Finis Pool). All other impoundments and MSUs rely on rainfall runoff to replenish water levels.

5.2.5 *Mosquito Control Ditches and Marsh Water Management*

Grid ditching of salt marshes was a common practice used to limit mosquito populations on the U.S. East Coast in the 1920s and 30s. Although the practice is no longer an accepted tool for mosquito control, the ditches continue to affect water levels and the biotic community in estuarine wetlands (James-Pirri et al. 2008). Some sections of the marsh in the southern and western portions of Bombay Hook NWR were grid-ditched in the 1930s, when mosquito control research was also taking place on the refuge. However, the majority of refuge area was not affected by this practice.

DNREC's Mosquito Control Section uses a variety of techniques to control mosquito populations in the county. These methods include use of insecticides and water management strategies known as open marsh water management (OMWM). OMWM practices are designed to physically alter formerly grid-ditched marshes so there is a reduction in habitat for mosquito larvae and egg deposition. OMWM practices may be implemented in the degraded salt marsh areas on the southern portion of the refuge but not in more pristine areas (Bombay Hook NWR staff, personal communication).

Table 7. Water Control Structures. From Refuge Water Management Data (2012).

Number	Name	Type	Flow	Size	Condition	Comments	Latitude	Longitude
0	Finis North WCS Gage	Gauging Station		0 Undefined	Fair	NOT GPS'ED LOCATION! NEED TO COLLECT! ALSO, ELEVATION!! ALSO, RENAME TO MATCH SWIM2 DATABASE!!	39.271919	-75.49028877
0	Raymond WCS Gage	Gauging Station		0 Undefined		NOT GPS'ED, NEED TO GET BETTER LOCATION; NEED TO CHANGE NAME TO MATCH SWIM DATABASE, GET ELEVATION,	39.2563369	-75.46061701
0	Sheariness WCS Gage	Gauging Station		0 Undefined		NOT GPS'ED, NEED BETTER LOCATION! CHANGE NAME TO MATCH SWIM DATABASE, GET ELEVATION, ETC!	39.2667284	-75.46472565
0	Bear Swamp WCS Gage	Gauging Station		0 Undefined		NOT GPS'ED... COMPLETELY IN WRONG SPOT, I SUSPECT! CHANGE NAME TO MATCH SWIM, GET ELEVATION, ETC!	39.2934322	-75.47985431
0	DU MSU N WCS	Boardstop	Outflow	0 Undefined	Good	not sure about info, type etc!	39.2810662	-75.48593438
10020880	Finish South WCS	Boardstop	Outflow	0 Undefined	Good		39.2697104	-75.49053587
10020881	Finish North WCS	Boardstop	Outflow	0 Undefined	Fair		39.2719203	-75.49015232
10020900	Sheariness East WCS	Boardstop	Outflow	0 Undefined	Good		39.2665437	-75.46408544
10020901	Sheariness North WCS	Boardstop	Outflow	0 Undefined	Good		39.2769009	-75.47995674
10020899	Raymond WCS east	Boardstop	Outflow	0 Undefined	Good		39.2563726	-75.46045557
10020877	Bear Swamp North WCS	Boardstop	Outflow	0 Undefined	Fair		39.2935332	-75.47988616
10020875	Raymond Dike	Dam		0 Undefined	Good		39.2604593	-75.46205093
10020882	Dike / Causeway Rd Bear Swamp Ditch	Dam		0 Undefined	Good		39.2783437	-75.47973344
10020892	Sheariness Dike	Dam		0 Undefined	Good		39.2728651	-75.47048888
10020902	Bear Swamp Canal WCS	Boardstop	Outflow	0 Undefined	Fair		39.277324	-75.4795249
10020925	Bear Swamp Dike	Dam		0 Undefined	Good		39.2893094	-75.47534468
10020938	Raymond/Sheariness WCS	Boardstop		0 Undefined	Good		39.2630162	-75.46880083
10020940	Bear Swamp South WCS	Boardstop	Outflow	0 Undefined	Good		39.2810826	-75.4781491
0	Pool B Pump & Well	Pump-Well	Outflow	0 Undefined	Fair		39.281792	-75.48777856
0	Finnis Dike	Dam		0 Undefined	Good		39.2710523	-75.4902809
10020876	Raymond North WCS	Boardstop		0 Undefined	Failed		39.2646214	-75.46578428
10020968	Drainage Canal - Sheariness Impoundment	Undefined		0 Undefined	Good		39.2634901	-75.46944214
0	???????	Ditch Plug	Outflow	36 Inches	Fair	Aluminum CMP WCS 36" Diameter, 48" Deep, Culvert 18" X 30' Aluminum CMP	39.2802888	-75.49150583
0	Field 21 WCS	Boardstop	Outflow	0 Feet	Good		39.2818204	-75.49704392
0		Culvert	Outflow	18 Inches	Fair	Concrete 18" X21'	39.2831873	-75.49724156
0	Field 109 WCS	Boardstop	Outflow	0 Undefined	Fair		39.290595	-75.5026323
0	Field 108 WCS	Boardstop	Outflow	0 Undefined	Failed	WCS Mowed off	39.2885487	-75.50163603
0		Boardstop	Outflow	0 Undefined	Good		39.2854142	-75.50010683
0	Field 19 WCS	Boardstop	Outflow	0 Undefined	Fair		39.2863223	-75.49692473
0	Field 22 WCS	Boardstop	Outflow	0 Undefined	Good		39.2871372	-75.49507384
0		Culvert		0			39.2845036	-75.50685779
0		Culvert		0			39.284636	-75.50974535
0		Culvert		0			39.2847768	-75.51246193
0		Culvert		0			39.2845597	-75.50390484
0		Culvert		0			39.2849195	-75.50024933
0		Culvert		0			39.2839795	-75.48793262
0		Culvert		0			39.2804176	-75.49066663
0		Culvert		0			39.2765151	-75.49086411

Note: Three additional boardstops were digitized from maps provided by refuge staff that are not included in the table above. They are 1) south of Big Woods Pond, 2) east of Field 23 MSU and 3) southwest of B-Pool (WMU-6).

5.2.6 Roads

18.2 miles of roads are maintained within current refuge boundaries (Figure 4). Most lie in the upland areas located in the northeast section of the refuge, and follow impoundment dikes. Roads can have a negative impact on refuge water resources where they act as dikes or create choke points that limit water movement in tidal and non-tidal stream channels. These features can limit the natural inundation patterns in refuge wetlands and contribute to stream channel erosion. In some areas of the refuge, like the

Air Force Tract, there are roads causing habitat fragmentation and localized flooding problems. In general, the refuge road network is not considered a major threat to refuge water resources.

5.3 Water Quality

Water quality information included in the WRIA is derived from the Reach Access Database (RAD) maintained by the U.S. Environmental Protection Agency (EPA). Additional data is publically available at the EPA's "Envirofacts" website. These databases were used to collect information on listed waters and National Pollutant Discharge Elimination System (NPDES) permits in and around Bombay Hook National Wildlife Refuge (Figure 8).

Section 303(d) of the Clean Water Act requires that each state identify water bodies where water quality standards are not met. DNREC develops lists of known water quality limited rivers and lakes. One stream, the Leipsic River, at Bombay Hook NWR has been identified as an impaired waterbody in Delaware's 303(d) list (Table 8).

Table 8. Listed waterbodies at the Bombay Hook National Wildlife Refuge. From EPA RAD database.

List ID	Waterbody Name	Latest Listing	Impairment
DE160-001 (A)	Leipsic River	2006	Total Coliform, Dissolved Oxygen, Nutrients

For the most recent year of listing (2006), the Leipsic River was identified as being impaired due to levels of total coliform, dissolved oxygen, and nutrients. Total Coliform is a measure of pathogens that can be harmful to human health. Elevated levels of pathogens are associated with concentrated stormwater runoff, septic system outfall, and marina discharges. Low dissolved oxygen levels often are a result of increased nutrient loads that enters waterways from nearby agricultural operations. DNREC developed Total Maximum Daily Loads (TMDLs) for the Leipsic River which were approved by the EPA in 2008. The TMDL for the river sets load allocations for nitrogen, phosphorus, and *Enterococcus* (DNREC 2006a, 2006b).

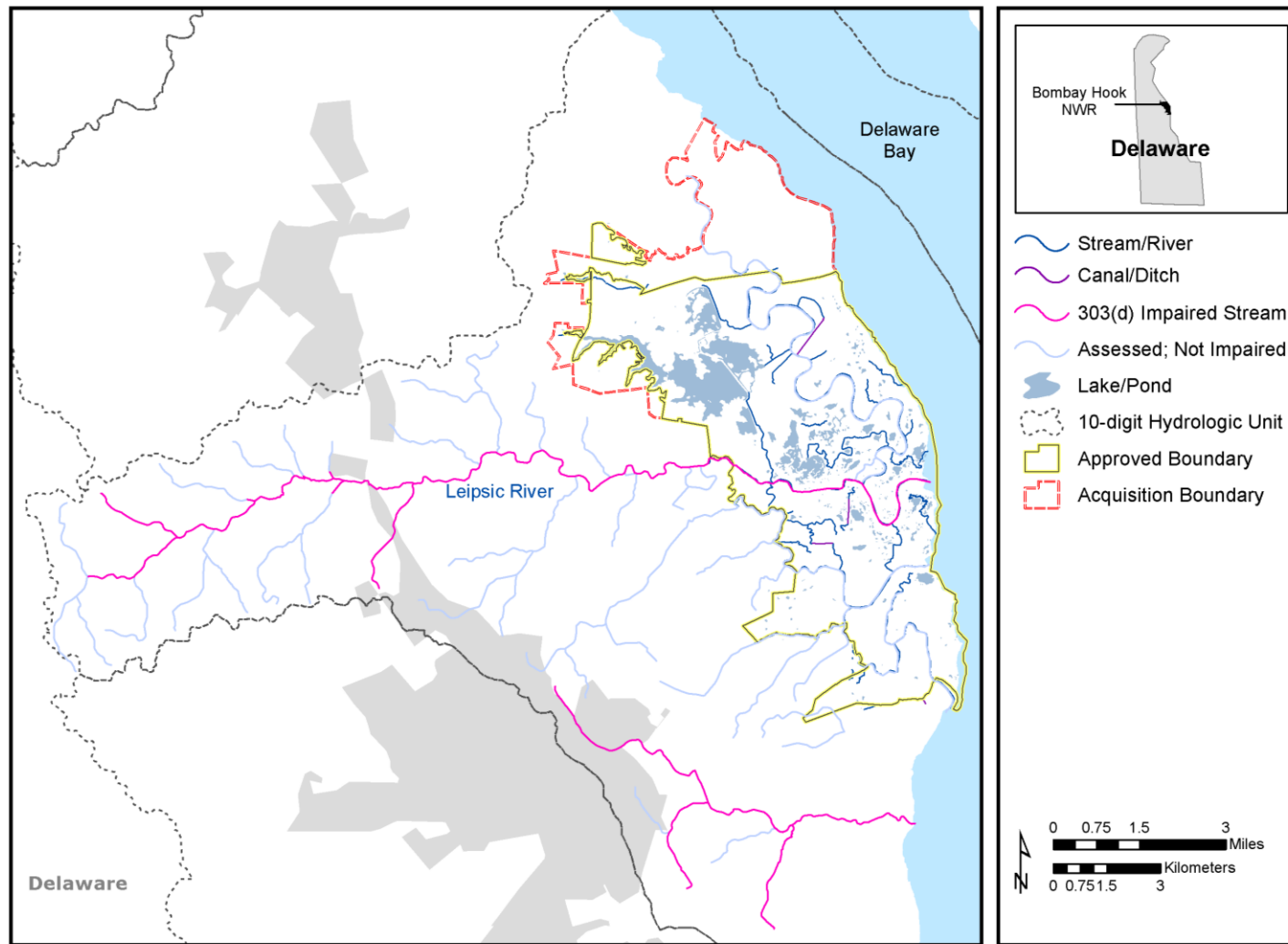


Figure 8. EPA listed waters from the EPA's RAD database.

NPDES permits are issued to businesses by DNREC to regulate the quality and quantity of pollutants discharged into waters of the United States. Stormwater and treated wastewater are two examples of discharges regulated under the NPDES program. There are no NPDES permits from the EPA's RAD database within the 10-digit HU.

Water quality concerns at the refuge were summarized in the 2004 Contaminants Assessment Report prepared by the Chesapeake Bay Field Office, Annapolis, MD (McGowan 2004). The report concludes that the major water quality threats to the refuge are contaminated agricultural/urban runoff and petroleum spills in the Delaware Bay. Of particular concern is the potential for nutrient and pesticide contamination in Finis Branch, the primary freshwater supply for refuge impoundments.

Review of water quality information for Delaware indicates that excessive nutrients leading to eutrophication of surface waters is one of the greatest water quality concerns in Delaware (DNREC 2005). Fertilizer application on agricultural land and waste generated from poultry facilities are the primary sources. To address nutrient contamination, the Delaware Department of Agriculture has created a Nutrient Management Program to facilitate practices that can limit nutrient contamination of surface water and groundwater. The western edge of the refuge is bordered by agricultural land that can be a source of sediment-laden runoff in the spring (Bombay Hook NWR staff, personal communication). Because of their proximity to agricultural fields, water resources on the western edge of the refuge are more likely to be compromised by elevated levels of nitrogen and phosphorus in surface water and groundwater. If there are eutrophication problems due to excessive nutrients it is expected they would manifest in the refuge's freshwater impoundments.

5.3.1 Groundwater Contamination

In 2007, site inspections were conducted on refuge property formerly owned by the Department of Defense: the Dover Air Force Base Precision Bomb Range (northwest portion of the refuge near impoundments) and Dover Survival Training Annex (current Air Force Tract). Groundwater on the properties was analyzed for the presence of munitions constituents. Groundwater sampling found that lead levels in groundwater at the Air Force Tract exceeded screening values (Alion Science and Technology 2007a, 2007b). In a separate study, DNREC (2004) rated one of Bombay Hook NWR's public supply wells (Well No. 190556) as having a high susceptibility to metals due to land use activities and observed analytical data because the well water had elevated iron concentrations.

5.4 Water Monitoring

WRIAs identify water-related monitoring that is taking place on, or near, wildlife refuges and fish hatcheries. For this preliminary review, the WRIA collects information stored in the USGS National Water Information System (NWIS) database. Water monitoring can be broadly categorized as either water quality or water quantity focused. Water quality

monitoring typically consists of collecting surface water or groundwater samples for chemical analyses in a laboratory or with sensors deployed in the field. Alternative protocols may use techniques such as aquatic invertebrate sampling as a proxy for water quality. Water quantity monitoring typically includes the flow rate in a stream or the water level in a groundwater aquifer. WRIAs also consider weather stations and tide gages as other types of water-related monitoring.

5.4.1 Water Quantity Monitoring

This review identified 35 water quantity monitoring sites near the refuge, including stream gages, groundwater wells, atmospheric sites and tidal gages (Table 9 and Figure 9). The majority of the sites are maintained by the USGS, however many of these are inactive. There are no active USGS surface water monitoring sites within the 10-digit HU which contains Bombay Hook NWR. The closest active USGS surface water gage is on the St. Jones River in Dover (Map ID 28 Figure 9).

Additional water quantity monitoring includes: USFWS staff gage observations at refuge impoundments (Map ID 14,15,16,18 Figure 9), DNREC water level and velocity monitoring in tidal channels (Map ID 16,17,19,20 Figure 9), and tide gages maintained by National Oceanic and Atmospheric Administration (NOAA) (Map ID 33), National Estuarine Research Reserve System (NERRS) (Map ID 30) and USGS (Map ID 31 and 32). Tidal monitoring by USGS at Murderkill River site also includes velocity and discharge observations.

Tidal monitoring by DNREC has focused on water level and water velocity monitoring at four sites in tidal channels in Bombay Hook's salt marshes. The point of contact for DNREC tidal monitoring at Bombay Hook is Bob Scarborough (bob.scarborough@state.de.us).

Table 9. Water quantity monitoring sites, including type and agency. Reflects information available on USGS National Water Information System (NWIS) Mapper website (2012), NOAA Tides and Currents website, FWS Water Management Data and Leathers et al. (2010). Site names underlined and in blue are hyperlinked. Sites with the same Map ID number are located very close to one another.

Map #	Site Number	Site Name	Category	Agency	Status	Measurements
1	392414075360901	Gc14-02	Groundwater	USGS	Active	MEASUREMENTS
1	392414075361001	Gc14-03	Groundwater	USGS	Active	MEASUREMENTS
2	392403075362101	Gc14-04	Groundwater	USGS	Active	MEASUREMENTS
3	1483200	BLACKBIRD CREEK AT BLACKBIRD, DE	Stream Gage	USGS	Active	DAILY
4	392043075391201	Gc51-04	Groundwater	USGS	Active	MEASUREMENTS
5	1483400	SAWMILL BRANCH TR NEAR BLACKBIRD, DE	Stream Gage	USGS	Inactive	PEAK
6	392020075360501	Gc54-05	Groundwater	USGS	Active	MEASUREMENTS
7	391953075361201	Hc14-03	Groundwater	USGS	Active	MEASUREMENTS
8	391911075345201	Hd11-03	Groundwater	USGS	Active	MEASUREMENTS
9	1483290	PAW PAW BRANCH TRIBUTARY NEAR CLAYTON, DE	Stream Gage	USGS	Inactive	PEAK
10	1483300	PROVIDENCE CREEK AT CLAYTON, DE	Stream Gage	USGS	Inactive	MEASUREMENTS
11	1483350	MILL CREEK AT SMYRNA, DE	Stream Gage	USGS	Inactive	MEASUREMENTS
12	n/a	Smyrna, DE	Atmosphere	DEOS	Active	
13	391804075305101	Hd14-01	Groundwater	USGS	Active	MEASUREMENTS
14	n/a	Bear Swamp WCS Gage	Gage	FWS		
15	n/a	Finis North WCS Gage	Gage	FWS		
16	n/a	Sheariness Tide Gage	Gage	DNREC		
16	n/a	Sheariness WCS Gage	Gage	FWS		
17	n/a	Leatherberry Flats	Gage	DNREC		
18	n/a	Raymond WCS Gage	Gage	FWS		
19	n/a	Dock Site	Gage	DNREC		
20	n/a	Navigation Light	Gage	DNREC		
21	1483500	LEIPSIC RIVER NEAR CHESWOLD, DE	Stream Gage	USGS	Inactive	DAILY
22	391217100000000	Evans Farm	Atmosphere	USGS	Inactive	

Water Resources Inventory and Assessment
Bombay Hook National Wildlife Refuge

February 2013

23	1483650	FORK BRANCH AT DUPONT, DE	Stream Gage	USGS	Inactive	MEASUREMENTS
24	1483655	FORK BRANCH NEAR DOVER, DE	Stream Gage	USGS	Inactive	MEASUREMENTS
25	1483680	MAIDSTONE BRANCH AT DUPONT, DE	Stream Gage	USGS	Inactive	MEASUREMENTS
26	1483670	MUDSTONE BRANCH AT CHESTNUT GROVE, DE	Stream Gage	USGS	Inactive	DAILY
27	391026075304901	Id55-01	Groundwater	USGS	Active	MEASUREMENTS
28	1483700	ST JONES RIVER AT DOVER, DE	Stream Gage	USGS	Active	DAILY
29	390920100000000	U.S.GEOLOGICAL SURVEY OFFICE AT DOVER, DE	Atmosphere	USGS	Inactive	
30	SCLD1	Scotton Landing	Tidal	NERRS	Active	
31	1484085	Murderkill River at Bowers, DE	Tidal	USGS	Active	
		DELAWARE BAY AT SHIP JOHN SHOAL LIGHTHOUSE,				
32	1412350	NJ	Tidal	USGS	Active	DAILY
33	8551910	Reedy Point, DE	Tidal	NOAA	Active	

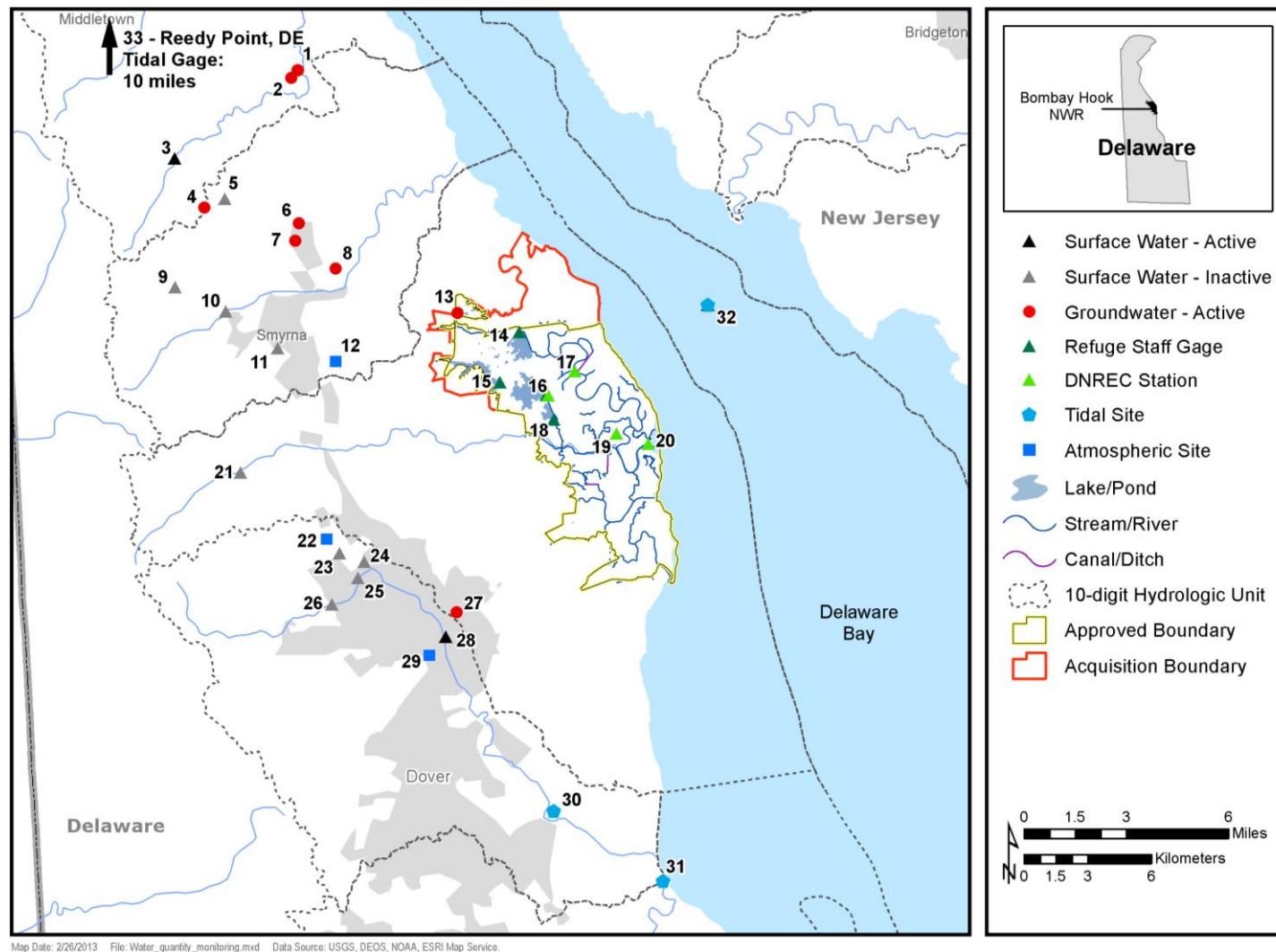


Figure 9. Water quantity monitoring site locations near Bombay Hook NWR.

5.4.2 *Water Quality Monitoring*

The USGS NWIS database identifies 19 water quality monitoring sites near the refuge, many of which are inactive (Table 10, Figure 10). There are no active USGS surface water quality monitoring sites on the refuge or within the 10-digit HU. There is one active USGS groundwater monitoring well in the northwest portion of the refuge (Map ID 9 in Table 10 and Figure 10), but samples have not been collected since 1989. There is one DNREC continuous surface water quality monitoring site on the Leipsic River west of the refuge (Map ID 15 in Table 10 and Figure 10). Data for sites monitored by DNREC are available online at <http://www.deos.udel.edu/odd-divas/wquality.php>.

Additionally, in Sussex County, DNREC maintains the Coastal Sussex Saltwater Monitoring Network, which is composed of approximately 30 wells used to monitor coastal aquifers for saltwater intrusion (Barlow 2003, DNREC undated). The network was established following the publication of two USGS studies (Phillips 1987, Phelan 1987) and currently includes public supply wells in New Castle County and southern Sussex County. Kent County wells are not included in the network; although some wells in the county are known to have issues with saltwater intrusion (DNREC staff, personal communication).

Table 10. Water quality monitoring sites, including type, agency and period of record. Reflects information available on USGS National Water Information System (NWIS) Mapper website (2012), NOAA Tides and Currents website, Alion Science and Technology (2007a,b), EPA's STORET database and DNREC Water Quality Monitoring Portal. Site names underlined and in blue are hyperlinked.

Map #	Site Number	Site Name	Category	Agency	Status
1	392414075360901	Gc14-02	Groundwater	USGS	Active
1	392414075361001	Gc14-03	Groundwater	USGS	Active
2	392403075362101	Gc14-04	Groundwater	USGS	Active
3	1483200	BLACKBIRD CREEK AT BLACKBIRD, DE EPHEMERAL POND 1 (SITE 1) NR VANDYKE, DE	Stream Site	USGS	Active
4	392046075443401	VANDYKE, DE	Lake Site	USGS	Active
5	391953075361201	Hc14-03	Groundwater	USGS	Active
6	391911075345201	Hd11-03	Groundwater	USGS	Active
7	1483300	PROVIDENCE CREEK AT CLAYTON, DE	Stream Site	USGS	Inactive
8	1483348	MILL CREEK NEAR SMYRNA, DE	Stream Site	USGS	Inactive
9	391804075305101	Hd14-01 DELAWARE BAY AT SHIP JOHN SHOAL LIGHTHOUSE, NJ	Groundwater	USGS	Active
10	1412350		Tidal	USGS	Active
	DAB-AR-GW-100-				
11	02	Allee House	Groundwater	USFWS	Inactive
	DAB-AR-GW-100-				
12	01	Refuge HQ	Groundwater	USFWS	Inactive
13	1483500	LEIPSIC RIVER NEAR CHESWOLD, DE	Stream Site	USGS	Inactive
14	391354075344301	ALSTON BRANCH NEAR CHESWOLD, DE	Stream Site	USGS	Inactive
15	202031	Leipsic River @ Denny St. (Rt. 9)	Stream Site	DNREC	Active
16	1483650	FORK BRANCH AT DUPONT, DE	Stream Site	USGS	Inactive
17	1483655	FORK BRANCH NEAR DOVER, DE	Stream Site	USGS	Inactive
18	391200075313801	MUDDY BRANCH NEAR DOVER, DE	Stream Site	USGS	Inactive
19	1483680	MAIDSTONE BRANCH AT DUPONT, DE	Stream Site	USGS	Inactive
20	DSA-GR-GW-15-01	Air-to-ground gunnery range	Groundwater	USFWS	Inactive
21	DSA-SA-GW-15-01	Rifle range	Groundwater	USFWS	Inactive
22	DSA-BA-GW-15-1	Burn area – north	Groundwater	USFWS	Inactive
23	DSA-BA-GW-15-02	Burn area – southeast	Groundwater	USFWS	Inactive
24	1483666	Penrose B nr Pearsons Corner, DE	Stream Site	USGS	Active
25	1483700	ST JONES RIVER AT DOVER, DE	Stream Site	USGS	Active
26	SCLD1	Scotton Landing	Tidal	NERRS	Active

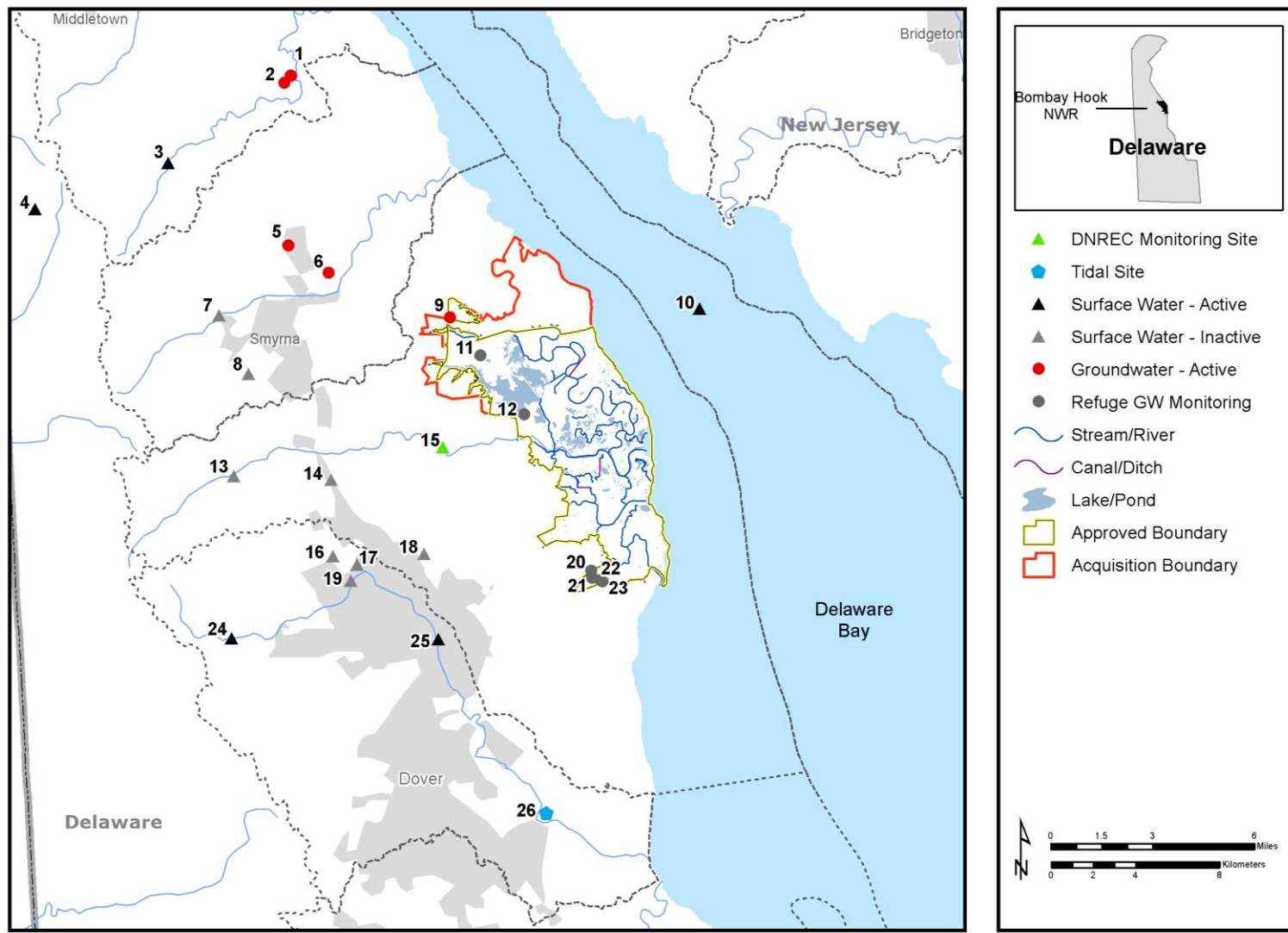


Figure 10. Water quality monitoring site locations near Bombay Hook NWR.

5.4.3 Tidal Monitoring

The nearest NOAA Delaware tide gage to Bombay Hook NWR is Station 8537121, located at Ship John Shoal, New Jersey, approximately 2.5 miles from the shore of the refuge, within Delaware Bay (Map ID 18 in Table 9 and Figure 9). Mean tidal range is 5.61 feet and diurnal range is 6.21 feet. The station was established in 1997, and while long-term tidal and sea level data are not available, it has been estimated that the mean sea level difference between sampling periods of 1960-1978 and 1983-2001 at this location is 0.18 feet.

Long-term sea level trends are available from the NOAA Station 8551910 at the Reedy Point Pier in Delaware, which is located approximately 20 miles north of Bombay Hook NWR (Map ID 17 in Table 9 and Figure 9). Seasonal changes in local sea level measured at the Reedy Point tide gage indicate bay levels are at their highest between August and October and lowest between December and February (Figure 11). The difference between the mean monthly maximum and minimum sea level in Figure 11 is approximately 0.20 meters (7.9 inches). Seasonal changes are a function of dominant weather patterns that drive water into or out of Delaware Bay. These seasonal water level changes are caused by changing ocean currents, increased runoff, and thermal expansion of water.

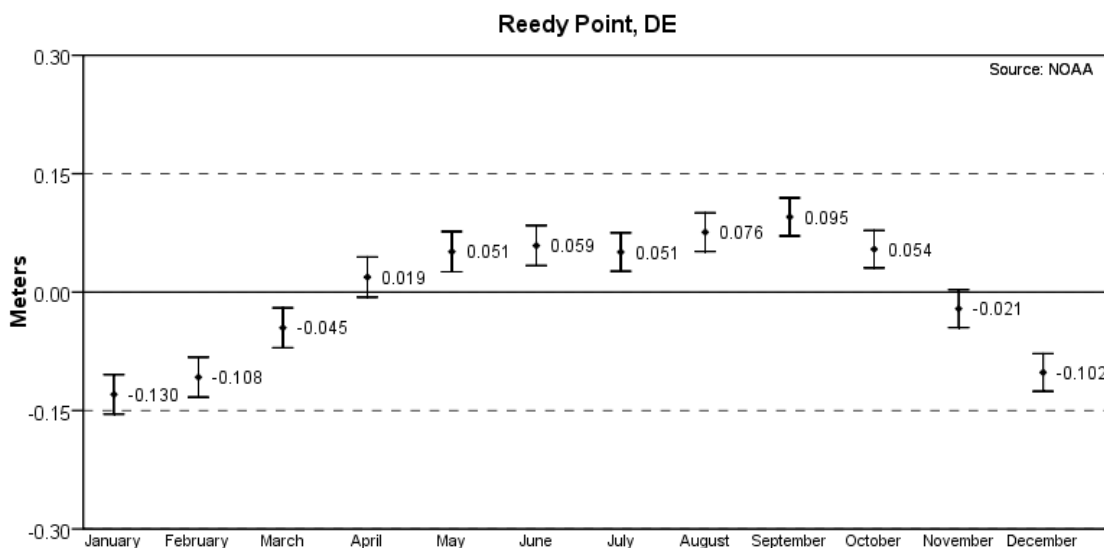


Figure 11. Average monthly variation in mean sea level due to temperature, ocean currents, and weather patterns. Graph is from the station's website ([link](#)).

5.4.4 Water Monitoring Data Gaps

Although there is a good amount of monitoring taking place near the refuge, data gaps still exist. The most obvious is the absence of any surface water quantity and quality monitoring on streams entering the refuge. Finis Branch is a high priority site for additional monitoring because it is the primary source of surface water for refuge

impoundments. Monitoring with an emphasis on quantifying nutrient and sediment inputs to Finis Pool will help to evaluate some of the impacts of neighboring agricultural fields.

DNREC's tidal channel flow monitoring may be a useful tool for evaluating conditions that contribute to salt marsh loss. It will be necessary to continue collaborating with DNREC on this work to further evaluate flow patterns and water level fluctuations in the tidal channels at Bombay Hook.

5.5 Water Rights

The laws governing water use in the State of Delaware are outlined in statute 7, Section 6001 of the Delaware Code. Water use regulations are described in the following document: Regulations Governing the Allocation of Water (DNREC 1987). This document is available online and is summarized below.

The Delaware Code establishes that water is an asset of the State and the State has the responsibility of managing water resources for the public benefit. DNREC is the state agency responsible for managing Delaware's water resources and has the power to adopt and enforce rules and regulations to control, conserve, and manage the waters of the State in the public interest (DNREC 1987).

Delaware does not give priority to different water uses. All uses have equal standing provided the use is "beneficial." Meaning, the water is used in a non-wasteful way and does not impair other water allocations (DNREC 1987). Water use permits are required for any diversions from surface water bodies and groundwater aquifers that exceed 50,000 gallons per day (gpd). The [Water Allocation Branch](#) of DNREC's Water Supply Section is responsible for administering the water allocation permitting program. DNREC evaluates permit applications and considers the proposed use relative to other users of the same water source. Permits are typically approved if DNREC determines there is adequate supply and the allocation will not harm other users. For surface water, withdrawals are limited to rates which:

- do not interfere with other permitted withdrawals unless compensation for injury is provided
- allow dilution and flushing of waste discharge and maintain adopted water quality standards
- protect valuable fish and wildlife
- maintain adequate flow over spillways of downstream impoundments
- prevent intrusion of saline waters where such intrusion threatens ground or surface water supplies; and
- provide other ecological, recreational, aesthetic, and private benefits which are dependent upon surface water flows

For groundwater, withdrawals are limited to rates that will not cause:

- long-term progressive lowering of water levels, except in compliance with management water levels established by DNREC
- significant interference with the withdrawals of other permit holders unless compensation for such injury is provided
- violation of water quality criteria for existing or potential water supplies
- significant permanent damage to aquifer storage and recharge capacity
- substantial impact on the flow of perennial streams below those rates specified for surface waters in the surface water withdrawal limits.

Permits are valid for 30 years from the time they are issued and are reviewed every 5 years. Permits can be transferred to other users or amended to address changes in water use. Any changes to existing permits trigger additional review by DNREC (Cocke personal communication). Permit holders are required to submit annual water use reports to DNREC summarizing the volume of water used for each month. For irrigation water users, only the volume of water used from March through November needs to be reported.

The only freshwater uses at Bombay Hook large enough to exceed the 50,000 gpd threshold are the storage of water in refuge impoundments. However, this use is not technically a diversion of surface water or groundwater and is not expected to require a water allocation permit.

5.5.1 Water Use Conflicts

Disputes over water allocation are handled on a case by case basis. An injured party can petition DNREC for an alternative water supply. This triggers a review by DNREC and the dispute is addressed through an administrative hearing. The Secretary of DNREC will issue a ruling on the case which can be appealed to the Environmental Review Board for a final decision (Cocke personal communication).

Water use permit review is handled by the DNREC's Water Allocation Branch. Notice of new water use permit applications are published in local newspapers (Cocke personal communication). It is expected that there will be a review period for new water use permits and during that time DNREC will consider public comments on the applications. If the Service has concerns about new water use permits it will be necessary to register those concerns with DNREC during the permit review period

5.6 Climate Trends

A variety of datasets exist that can be used to evaluate long-term climate trends at refuges in Region 5. Some of these data are included in the WRIA to provide a preliminary analysis of trends in precipitation, temperature, and stream runoff. Data were analyzed for trends using the nonparametric Mann-Kendall statistical test. This test can be used to

determine if there is a linear trend in a dataset and whether or not that trend is statistically significant ($p < 0.05$) (Helsel and Hirsch 2002).

5.6.1 U.S. Historical Climatology Network (USHCN)

The USHCN is a network of climate monitoring sites maintained by the National Weather Service. Sites in the network are selected because their location and data quality make them well suited for evaluating long-term trends in regional climate. The closest site to Bombay Hook NWR is located in Dover, DE. Data from the site illustrates trends in precipitation and air temperature in coastal Delaware over the last 115 years (Figures 12 – 15).

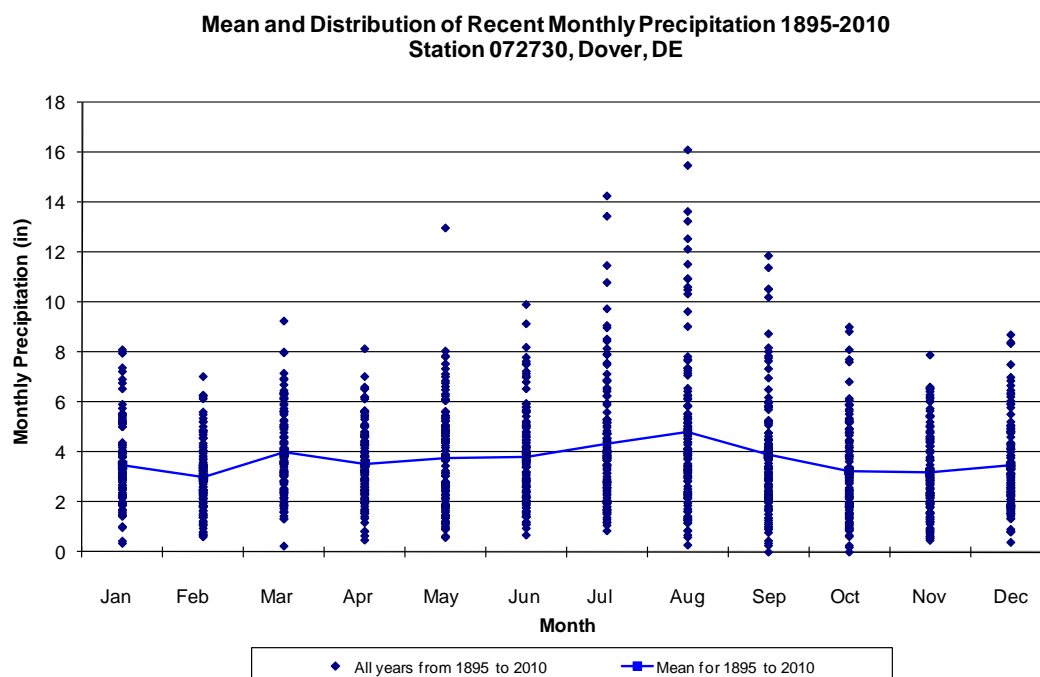


Figure 12. Distribution of total monthly precipitation at USHCN site 072730, Dover, DE. 1895-2010.

Trends presented in Figure 12:

- Relatively uniform precipitation distribution across the year. Precipitation in the summer months June – September appears to be higher than other months of year.
- Average monthly precipitation in Dover, DE is 3.71 inches.
- Average water year precipitation is 44.5 inches.

Precipitation patterns were evaluated by calculating the difference between each year's average precipitation and the average for all years. Presented as a percent, this approach can be used to identify years of above average, or below average, precipitation (Figure 13).

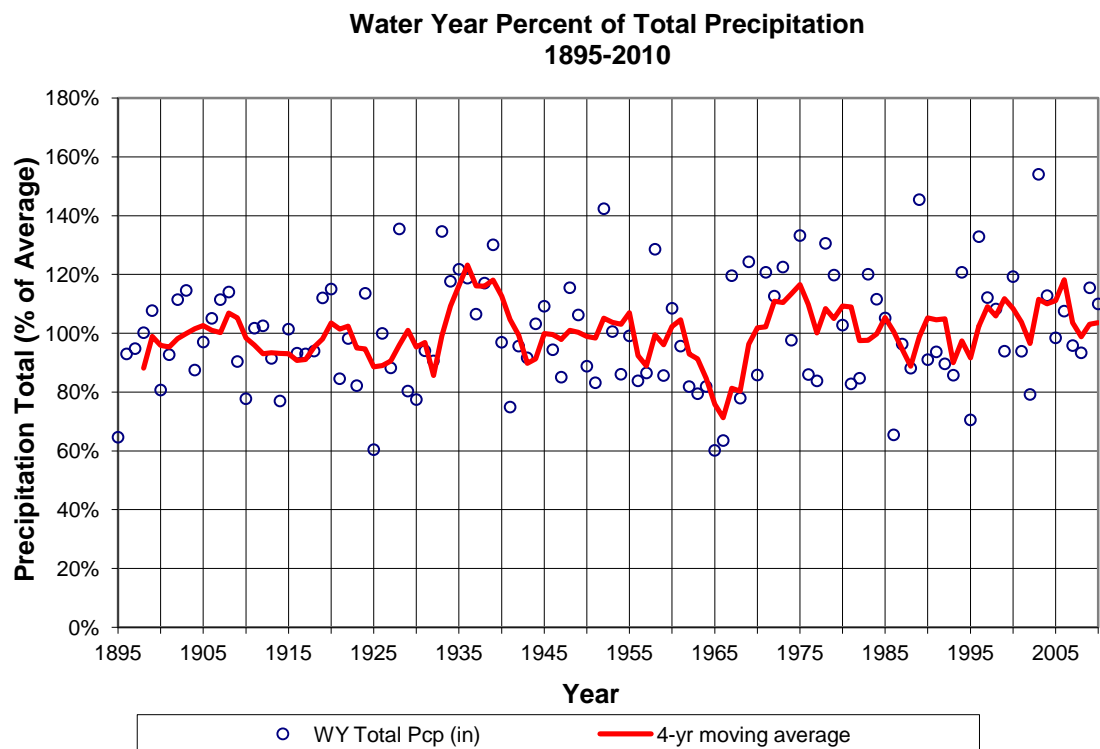


Figure 13. Percent of total Water Year precipitation at the Dover, DE USHCN site between 1895 and 2010.

Note: “Water Year” runs from October 1 through September 31. It is commonly used to track hydrologic data.

- The 1960s drought that affected the U.S. Northeast (Seager et al. 2012) shows up clearly in this record.
- Precipitation totals have regularly been above average, since the 1960s drought which agrees with observations at other weather stations in the U.S. Northeast (Seager et al. 2012).
- Water year precipitation totals at the Dover, DE site do not show a statistically significant trend between 1895 – 2010.

Monthly temperatures at the Dover, DE USHCN site were also reviewed to identify any patterns in air temperature since 1895 (Figure 14).

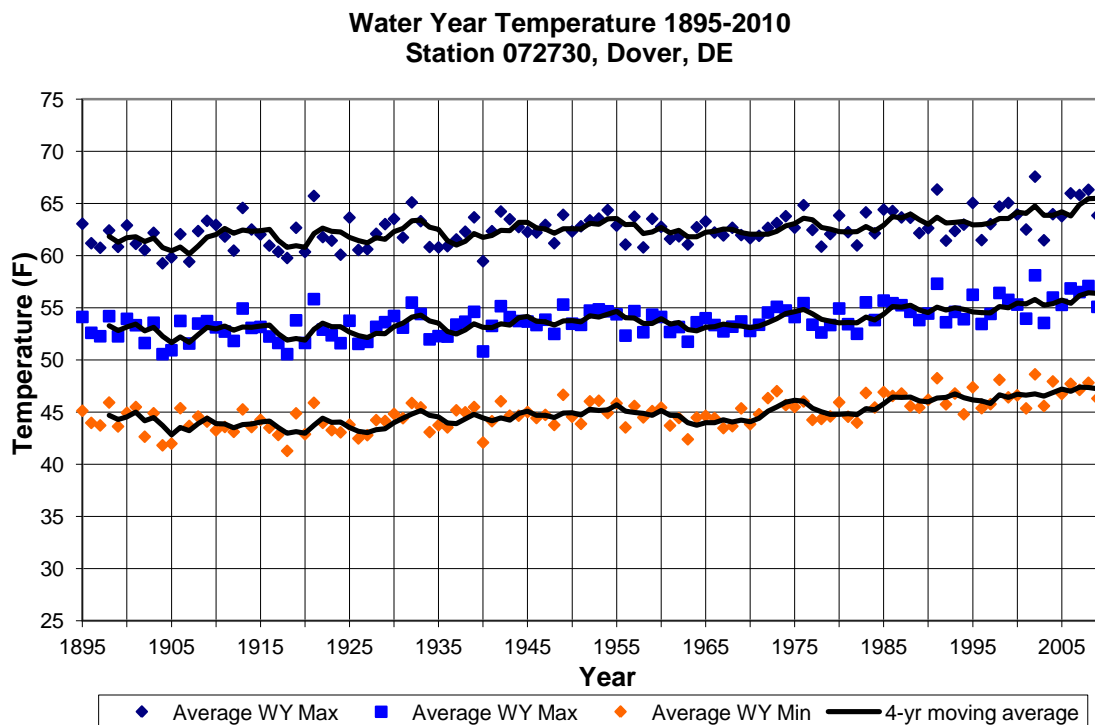


Figure 14. Average temperatures for the Water Year: 1895 – 2009 at the USHCN station in Dover, DE. The Water Year extends from 10/1 – 9/30 of a year.

Trends presented in Figure 14:

- Maximum air temperature has increased 2.8 °F during the period of record (statistically significant trend).
- Mean air temperature has increased about 2.9 °F during the period of record (statistically significant trend).
- Minimum air temperatures have increased about 3.2 °F during the period of record (statistically significant trend).

Maximum, mean, and minimum water year temperatures measured at the Dover, DE USHCN gage have all increased significantly since 1895. These trends agree with studies showing global temperatures are rising (Bates et al. 2008) and regional studies showing increasing air temperatures in the mid-Atlantic region of the United States (Polsky et al. 2000).

5.6.2 Streamflow Trends

Flow patterns in the St. Jones River were evaluated by calculating the difference between each year's average discharge and the average for all years. Presented as a percent, this

approach can be used to identify years of above average, or below average, runoff (Figure 15).

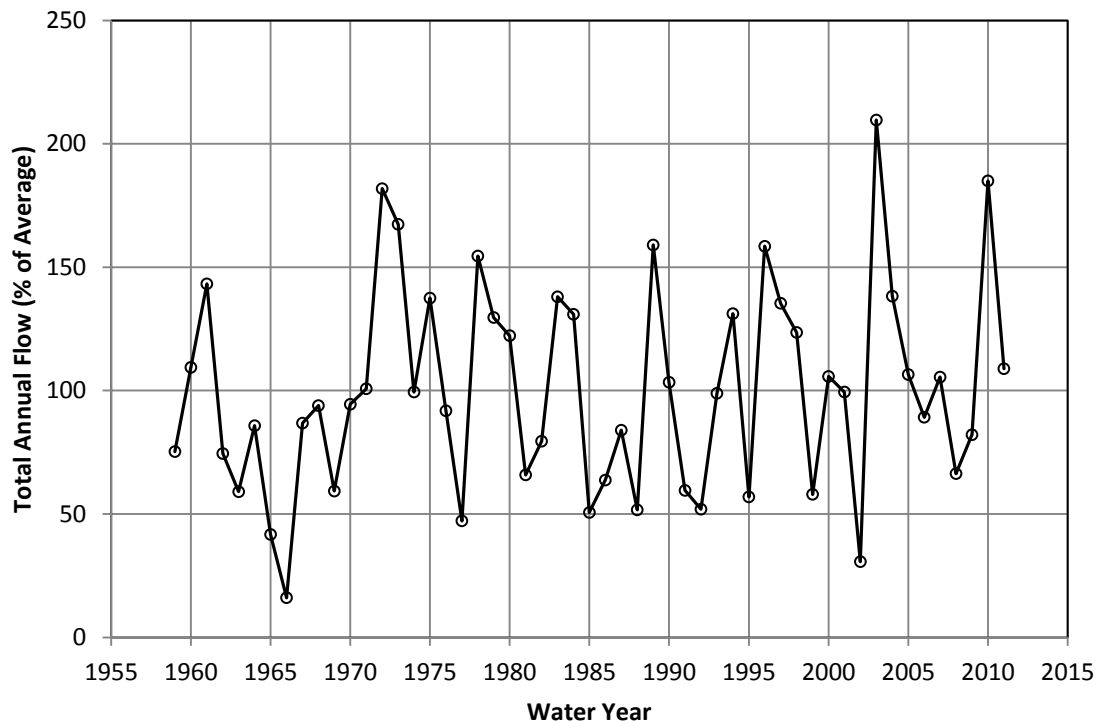


Figure 15. Percent of the average annual flow on the St. Jones River at Dover, DE: 1959-2011. Average annual flow from the period of record is 38 cubic feet per second (cfs). 1 cfs = 448.8 gallons per minute.

Trends presented in Figure 15:

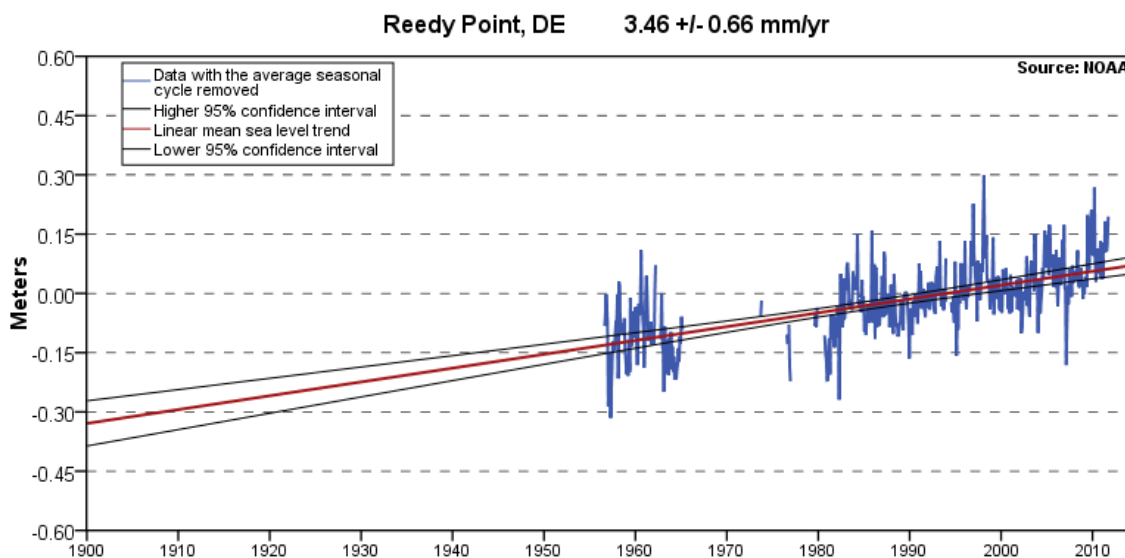
- The 1960s drought dramatically affected flow in the St. Jones River and remains the most pronounced period of below average flow.
- Highest water year flow for the year was observed in 2003.
- Lowest total flow for the year was observed in 1966.

Discharge data presented in this figure roughly correspond with total precipitation by water year data presented in Figure 13. Water year average discharge has not increased or decreased significantly over the period of record (1959 – 2012). The absence of a trend corresponds with a similar pattern in precipitation totals over the same period.

The strong response to drought conditions in the 1960s is similar to the response observed in many watersheds throughout the Northeast. This drought is considered the “drought of record” for the northeastern U.S. and droughts of similar magnitude and duration have not been observed before or since (Hayhoe et al. 2007, Seager et al. 2012).

5.6.3 Sea Level Trends

Long-term sea level trends are available from the NOAA Station 8551910 at the Reedy Point Pier in Delaware, which is located approximately 20 miles north of Bombay Hook NWR (Map ID 17 in Table 9 and Figure 9). Data from the Reedy Point tide gage suggests the local sea level is rising about 3.5 millimeters (0.14 inches) per year, which is an increase of about 5.5 inches since 1970 (Figure 16). This rate is about double the average global rate of 1.8 mm/yr (Horton and Miller 2010). Tide gages record a local measurement of sea level relative to a fixed point on land near the gage site. Sea level in Delaware is rising faster than the global average because the land surface is subsiding, or sinking, at a rate of 1.7 mm/year (Engelhart et al. 2009). Subsidence of the land surface in the mid-Atlantic is largely a response of the earth's crust to the melting of the Laurentide ice sheet over 10,000 years ago. The weight of the ice sheet caused the land surface in the mid-Atlantic to bulge upward. Once the ice sheet melted and its massive weight was removed from the earth's crust, land in the mid-Atlantic began to subside (Horton and Miller 2010).



The mean sea level trend is 3.46 millimeters/year with a 95% confidence interval of ± 0.66 mm/yr based on monthly mean sea level data from 1956 to 2006 which is equivalent to a change of 1.14 feet in 100 years.

Figure 16. Mean monthly sea level and linear trend at the Reedy Point, DE tide gage (Site No. 8551910). Graph is from the station's website ([link](#)).

Predictions of sea level rise in the Intergovernmental Panel on Climate Change (IPCC) report put the range of global sea level rise between 0.75 and 1.90 meters (2.46 - 6.23 feet) by 2100. Additionally, the land surface in the mid-Atlantic is expected to subside 0.1 and 0.2 meters (3.93-7.87 inches) by 2100 which will enhance these global sea level trends. The amount of local sea level rise and the impacts on estuaries at Bombay Hook NWR will depend on many factors including the morphology of the coast line and human modifications to the coast like tide gates and levees (Horton and Miller 2010). The Sea

Level Affecting Marshes Model (SLAMM) attempts to quantify these changes to coastal wetland habitat using data from NOAA tide gages, USFWS National Wetland Inventory maps, and USGS digital elevation models. For Bombay Hook NWR, SLAMM was used to predict wetland community changes by 2100 to five sea level rise scenarios: 0.39m, 0.69m, 1.0m, 1.5m, and 2.0m (1.3 - 6.6 feet) (Clough and Larsen 2010).

The SLAMM simulation of Bombay Hook NWR indicates a refuge susceptible to the effects of sea level rise especially at moderate-to-higher scenarios. The refuge is predicted to lose more than three quarters of its regularly flooded (salt) marsh in scenarios above 1 meter. Salt marsh is actually predicted to increase in lower SLR scenarios due to the conversion of irregularly flooded marshes. The refuge is predicted to lose between 23% and 62% of its dry land, and between 15% and 97% of its irregularly flooded marsh across all scenarios (Table 11).

Table 11. Predicted loss by 2100 from existing acreages rates for wetland habitat under different sea level rise scenarios. From the Bombay Hook NWR SLAMM report (Clough and Larson 2010).

SLR by 2100 (m)	0.39	0.69	1	1.5	2
Salt marsh	-1%	-7%	-9%	84%	94%
Undeveloped Dry Land	23%	31%	38%	50%	62%
Irregularly Flooded Marsh	15%	37%	83%	95%	97%
Estuarine Beach	2%	2%	2%	3%	95%
Swamp	28%	38%	45%	54%	64%
Inland Fresh Marsh	7%	10%	13%	18%	27%

For the changes presented in Table 11 to occur, the current rate of sea level rise will need to increase considerably. At the current rate of 3.46 mm/year, Bombay Hook NWR will not experience sea levels equivalent to any of the prediction scenarios by the year 2100. The 0.39m scenario would be achieved in the year 2124. The 2m scenario would be achieved in the year 2590.

5.6.4 Future Climate Predictions

The Intergovernmental Panel on Climate Change (IPCC) predicts the U.S. Northeast will experience earlier spring snowmelt and reduced summer runoff as the global climate warms in response to human emissions of greenhouse gasses (Bates et al. 2008, Mack 2008). Hayhoe et al. (2007) review historic climate data and climate change models to evaluate the Northeast's response to global climate change. Results of their analyses are summarized below:

Temperature

Air temperature records in the Northeast show consistent signs of warming since the 1970s with the greatest increases occurring during the winter months. Warming trends are expected to continue and rates of warming increase under different climate modeling scenarios. As temperatures warm the frequency of extreme warm temperatures will increase also.

Precipitation

Precipitation records in the US Northeast show a consistent increase in annual precipitation totals over the last century. Under different climate modeling scenarios winter precipitation is expected to increase while summer precipitation is expected to remain unchanged or decrease. Heavy, intense precipitation events are expected to become more common also.

Snowpack

The amount of snow cover has decreased across the Northeast in the last 30 years. This trend is expected to continue with less precipitation falling as snow in the winter months.

Streamflow Patterns

Since 1970, peak snowmelt runoff has occurred earlier in the year and the peak runoff values have been rising in winter and early spring. These patterns are expected to continue as wetter winters and warmer temperatures decrease winter snowpacks. The response to seasonal snowmelt will become less pronounced as more winter precipitation falls as rain. Peak flows are expected to be concentrated in the winter and early spring months and minimum streamflow will continue to be concentrated in the summer months. Minimum flows will be lower than the recent past and the duration of the summer low flow period is expected to increase.

Drought

Modeling scenarios predict that the frequency of severe, persistent drought (> 6 months) will remain at rates observed in the recent past. However, hotter drier summers and periodic precipitation deficits are expected to increase the frequency of short- (1-3 month) and medium-term (3-6 month) droughts. Periods of drought will be most pronounced at the end of the growing season in the late summer and early fall.

The climate trends discussed in Section 5.6 mirror the trends observed throughout the Northeast and mid-Atlantic (Hayhoe et al. 2007, Polsky et al. 2000). At Bombay Hook, management challenges that will be exacerbated by a warming climate include sea level rise, increased flooding, and increased short-term droughts.

Streamflow in the vicinity of Bombay Hook NWR is not dominated by snowmelt runoff and therefore changes in winter snowpack are not expected to affect the refuge water resources noticeably. However, warmer summer temperatures and longer growing seasons will probably increase the water demand plants place on the shallow groundwater aquifer which is an important driver of streamflow in Kent County streams. Additionally, warmer temperatures during the growing season will increase the water needs of agricultural crops which will increase the pumping demands placed on the Columbia Aquifer. Combined, these processes will likely result in less freshwater inputs to the refuge.

6 ASSESSMENT

6.1 Water Resource Issues of Concern

This section discusses the primary threats facing water resources at Bombay Hook NWR based on the inventory and supporting information collected for this report. For the purposes of this initial review, the primary water resources of interest are the wetlands, streams, and impoundments inside the refuge's acquisition boundary.

6.1.1 Groundwater Development

Groundwater development to support irrigated agriculture is widespread in the vicinity of Bombay Hook NWR. It is likely that groundwater pumping in the shallow Columbia Aquifer to the west of the refuge helps reduce freshwater inflow in the small brooks and runs that enter the refuge. Reduced freshwater inflows can compromise water quality on refuge water resources by concentrating nutrients, increasing temperature, and facilitating landward movement of saltwater from Delaware Bay. Impacts from groundwater development will probably be most pronounced in the impoundments where freshwater from off-refuge sites first enters the refuge on its western boundary.

6.1.2 Excessive Nutrients in Groundwater and Surface Water

Excessive nutrients in Delaware's groundwater and surface water is a major concern in the state (DNREC 2005). In addition to the Leipsic River, it is likely that the small brooks and creeks entering the refuge are also impaired due to excessive nutrients. Additionally, shallow groundwater throughout much of Delaware is contaminated by nutrients that seep into the aquifer. In areas where impaired surface water and groundwater enters the refuge, the probability of algal blooms or excessive aquatic plant growth are high, which may compromise refuge water resources. Most likely the impacts of nutrient inputs will be most pronounced in refuge impoundments.

6.1.3 Sea Level Rise

The SLAMM report for Bombay Hook NWR predicts how refuge wetlands will change in response to sea level rise. The refuge can expect a shift in wetland habitat landward and will need to use that knowledge to prioritize future land acquisitions or management activities. Existing changes in sea level are probably already manifesting as habitat change near the saltwater / freshwater marsh interface. Stream channels and mosquito control ditches can act as conduits that allow saltwater to penetrate into freshwater wetland systems.

6.2 Needs and Recommendations

The threats to water resources at Bombay Hook NWR take on a range of importance depending on the time scale of interest and the other priorities of the Region. Because more than 80% of Bombay Hook NWR is estuarine marsh habitat, the loss of this habitat due to sea level rise is, of course, the most obvious long-term threat to the refuge. Less obvious, are changes to stream and groundwater inputs to the refuge's freshwater wetlands.

6.2.1 Evaluate Groundwater Development Adjacent to Refuge

Groundwater development for agricultural purposes is extensive in Kent County, DE and is thought to utilize the same water the refuge's freshwater streams and wetlands rely on. The State of Delaware maintains a database of water production wells. Information on how wells were completed and what they are used for can be requested from the DNREC. Recommend that the refuge prepare the forms necessary to acquire this information from the Department to evaluate groundwater use adjacent to the refuge. Depending on the number of wells and their proximity to refuge wetlands, this information can be used to identify which, if any, freshwater wetlands may be compromised by groundwater development.

6.2.1 Evaluate Potential Water Quantity and Water Quality Monitoring Sites at Bombay Hook NWR

Although some water quality monitoring is taking place in groundwater and surface water locations off refuge, there is little monitoring taking place on refuge water resources. The condition of water entering the refuge via Finis Branch seems particularly important since it is the primary stream contributing surface water to the refuge's impoundments. The need for streamflow stations in Kent and Sussex counties was also stated in a data gap analysis prepared for DNREC (Leathers et al. 2010). Additionally, the refuge may want to consider monitoring salinity in freshwater wetlands susceptible to saltwater intrusion.

6.2.2 Review Hydrologic Impacts of Refuge Infrastructure

Infrastructure like water control structures, culverts, bridges, ditches, and dikes affect water movement through refuge wetlands. In some cases poorly designed infrastructure or legacy infrastructure from pre-refuge land uses can create problems that compromise habitat management. The refuge's infrastructure should be evaluated from a hydrologic perspective to identify potential problem features. This information will be helpful as the refuge seeks to develop plans for adapting to climate change and rising sea levels.

7 REFERENCES

- Alion Science and Technology. 2007a. Site Inspection Report for Dover AFB Precision Bomb Range. DERP FUDS Project No, C03DE025101. Prepared for the U.S. Army Engineering and Support Center, Huntsville and the U.S. Army Corps of Engineers, Baltimore District. October 2007.
- Alion Science and Technology. 2007b. Site Inspection Report for Dover Survival Training Annex. DERP FUDS Project No, C03DE054602. Prepared for the U.S. Army Engineering and Support Center, Huntsville and the U.S. Army Corps of Engineers, Baltimore District. October 2007.
- Andres, A.S., 2001. Geohydrology of the Smyrna-Clayton Area, Delaware. Hydrologic Map No. 10. Delaware Geological Survey, University of Delaware.
- Andres, A.S., Howard, C.S., Keyser, T.A., and L.T. Wang. 2002. Digital Ground-Water Recharge Potential Map Data for Kent and Sussex Counties, Delaware.
<http://www.dgs.udel.edu/datasets/kent-and-sussex-water-recharge-data-digital-data-product-no-02-01>.
- Bates, B.C., Kundzewicz, Z.W., Palutikov, J, Wu S. 2008. Climate change and water. Technical Paper of the Intergovernmental Panel on Climate Change. IPCC Secretariat, Geneva. Available via
http://www.ipcc.ch/publications_and_data/publications_and_data_technical_papers.shtml Accessed July 23, 2012
- Barlow, P.M. 2003. Ground Water in Freshwater-Saltwater Environments of the Atlantic Coast. USGS Circular 1262. <http://pubs.usgs.gov/circ/2003/circ1262/>
- Clough, J.S. and Larson, E.C., 2010. Application of the Sea-Level Affecting Marshes Model (SLAMM 6) to Bombay Hook NWR. Prepared for Dr. Brian Czech, U.S. Fish and Wildlife Service.
http://warrenpinnacle.com/prof/SLAMM/USFWS/SLAMM_Bombay_Hook.pdf
- Cowardin, L.M., Carter, V., Golet, F.C., and E.T. LaRoe. 1979. Classification of wetlands and deepwater habitats of the United States. U.S. Fish and Wildlife Service. Washington, D.C.
- Delaware Department of Natural Resources and Environmental Control (DNREC). 1987. Regulations Governing the Allocation of Water. Delaware Department of Environmental Control, Dover, DE.
<http://www.dnrec.state.de.us/water2000/Sections/WatSupp/Library/alloc.pdf>
- DNREC. 2004. Public Water Supply Source Water Assessment for Bombay Hook Refuge.

- http://www.wr.udel.edu/swaphome/Publications/Final_assess/GroundWater/bombayhook.pdf.
- DNREC. 2005. Delaware Bay and Estuary Assessment Report: Whole Basin Report. Accessed online: <http://www.dnrec.delaware.gov/WholeBasin/Pages/DelBayReport.aspx>
- DNREC. 2006a. TMDLs for the Leipsic River Watershed, Delaware. <http://regulations.delaware.gov/AdminCode/title7/7000/7400/7421.pdf>
- DNREC. 2006b. Leipsic River Watershed Proposed TMDLs. Prepared by HydroQual, August 2006. http://www.dnrec.delaware.gov/swc/wa/Documents/TMDL_TechnicalAnalysisDocuments/7_LeipsicTMDLAnalysis.pdf
- DNREC. 2011. Eleventh Report to the Governor and General Assembly Regarding the Progress of the Delaware Water Supply Coordinating Council: Estimates of Water Supply and Demand for Kent County and Sussex County through 2030.
- DNREC. Undated. Water Supply Section – Ground Water Protection Branch. <http://www.dnrec.delaware.gov/wr/SERVICES/OTHERSERVICES/Pages/WaterSupplyGroundWaterProtectionProgram.aspx>
- Delaware Geological Survey (DGS). Undated. A Summary of the Geologic History of Delaware. <http://www.dgs.udel.edu/delaware-geology/summary-geologic-history-delaware>.
- dePaul, V.T., Rosman, R., and P.J. Lacombe. 2009. Water-level conditions in selected confined aquifers of the New Jersey and Delaware Coastal Plain, 2003. U.S. Geological Survey Scientific Investigations Report 2008-5145, 123 p., 9 pl. <http://pubs.usgs.gov/sir/2008/5145/pdf/SIR2008-5145.pdf>
- U.S. Environmental Protection Agency Reach Access Database (EPA-RAD) <http://epamap32.epa.gov/radims/>
- Engelhart, S.E., Horton, B.P., Douglas, B.C., Peltier, W.R., and T.E. Törnqvist. 2009. Spatial variability of late Holocene and 20th century sea-level rise along the Atlantic coast of the United States. *Geology* 37(12): 1115-1118. http://www.sas.upenn.edu/earth/bph/Res2009/Engelhart%20et%20al_Geology_2009.pdf
- EPA ‘Envirofacts’ website <http://www.epa.gov/enviro/>
- Hayhoe, K., Cameron, P.W., Huntington, T.G., Luo, L., Schwartz, M.D., Sheffield, J.,

- Wood, E., Anderson, B., Bradbury, J., DeGaetano, A., Troy, T.J., and D. Wolfe. 2007. Past and future changes in climate and hydrological indicators in the US Northeast. *Climate Dynamics*. 28: 381-407.
- Helsel, D.R., and Hirsch, R.M. 2002. Statistical methods in water resources. U.S. Geological Survey Techniques of Water-Resources Investigations, Book 4, Chapter A3.
- Horton, B. and K. Miller. 2010. Understanding sea level rise in the Mid-Atlantic. The Jersey Shoreline. Vol. 26. No. 4.
- James-Pirri, M.J., R.M. Erwin, and D.J. Prosser. 2008. US Fish and Wildlife Service (Region 5) Salt Marsh Study, 2001-2006: An assessment of hydrologic alterations on salt marsh ecosystems along the Atlantic coast. USGS Patuxent Wildlife Research Center and University of Rhode Island, Final Report to U.S. Fish and Wildlife Service, April 2008.
- Leathers, D. J., Scarborough, R. and D.R. Legates. 2010. A Data Gap Analysis and Inland Inundation Survey for the Delaware Coastline: Final Report and Recommendations. Submitted to DNREC March 15, 2010.
<http://www.deos.udel.edu/delawaregap/index.html>.
- Mack, T.J. 2008. Assessment of ground-water resources in the seacoast region of New Hampshire. U.S. Geological Survey Scientific Investigations Report 2008-5222.
- McGowan, P. 2004. Contaminants Assessment Report: Bombay Hook National Wildlife Refuge. U.S. Fish and Wildlife Service, Chesapeake Bay Field Office, Annapolis, MD.
- Menne, M.J., Williams, Jr., C.N., and R. S. Vose. 2011. United States Historical Climatology Network (USHCN) Version 2 Serial Monthly Dataset. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee.
- National Water Information System (NWIS) Mapper. U.S. Geological Survey. Available online at <http://wdr.water.usgs.gov/nwisgmap/>. Accessed 12/14/2011.
- Natural Resources Conservation Service (NRCS), United States Department of Agriculture. Soil Survey Geographic (SSURGO) Database for Kent County, Delaware. Available online at <http://soildatamart.nrcs.usda.gov>. Accessed 12/15/2011.
- NOAA NOS/CO-OPS (National Ocean Service/Center for Operational Oceanographic Products & Services)
<http://tidesandcurrents.noaa.gov/gmap3/>

- Phelan, D. J. 1987. Water levels, chloride concentrations and pumpage in the coastal aquifers of Delaware and Maryland. USGS Water-Resources Investigations Report 87-4229. <http://pubs.usgs.gov/wri/1987/4229/report.pdf>
- Phillips, S.W. 1987. Hydrogeology, degradation of ground-water quality, and simulation of infiltration from the Delaware River into the Potomac Aquifers, Northern Delaware. USGS Water-Resources Investigations Report 87-4185. <http://pubs.usgs.gov/wri/1987/4185/report.pdf>
- Polsky C., Allred J., Currit N., Crane R., and Yamal B. 2000. The Mid-Atlantic Region and its climate: past, present, and future. *Climate Research* 14: 161-173.
- PRISM Climate Group, Oregon State University, <http://prism.oregonstate.edu>, created 3 Feb 2010.
- Seager, R., Pederson, N., Kushnir, Y. and J. Nakamura. 2012. The 1960s Drought and the Subsequent Shift to a Wetter Climate in the Catskill Mountains Region of the New York City Watershed. *Journal of Climate*. 25: 6721-6742.
- Tiner, R.W. 1984. Wetlands of the United States: Current status and recent trends. U.S. Fish and Wildlife Service. National Wetland Inventory. Washington, D.C.
- Trapp, H., Horn, M.A. 1997. Groundwater Atlas of the United States: Delaware, Maryland, New Jersey, North Carolina, Pennsylvania, Virginia, West Virginia. HA 730-L. U.S. Geological Survey. http://pubs.usgs.gov/ha/ha730/ch_1/index.html. Last accessed: 1/31/12
- U.S. Fish and Wildlife Service (USFWS). 1994. Marsh and Management Plan: Bombay Hook National Wildlife Refuge. Smyrna, Delaware.